Effect of Mechanical Stress on GaN HEMT Gate Current: Experiment, Mechanisms, Models

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Gator Engineering
University of Florida

Outline

- Motivation
- Gate Leakage Measurements on Mechanically Stressed GaN HEMTs
- Experimental Analysis
- Simulation on GaN HEMT Gate Leakage Mechanisms
- Summary

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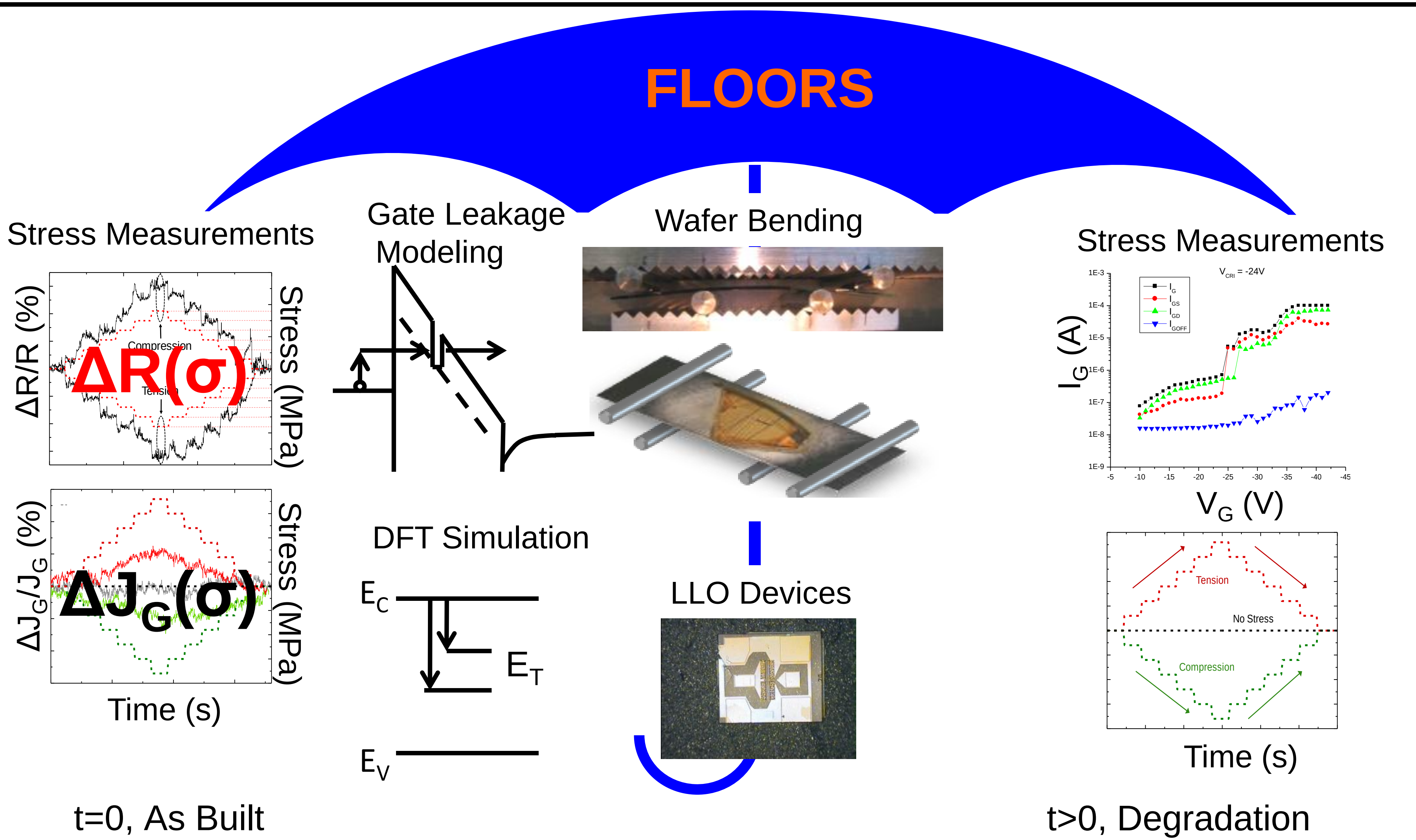
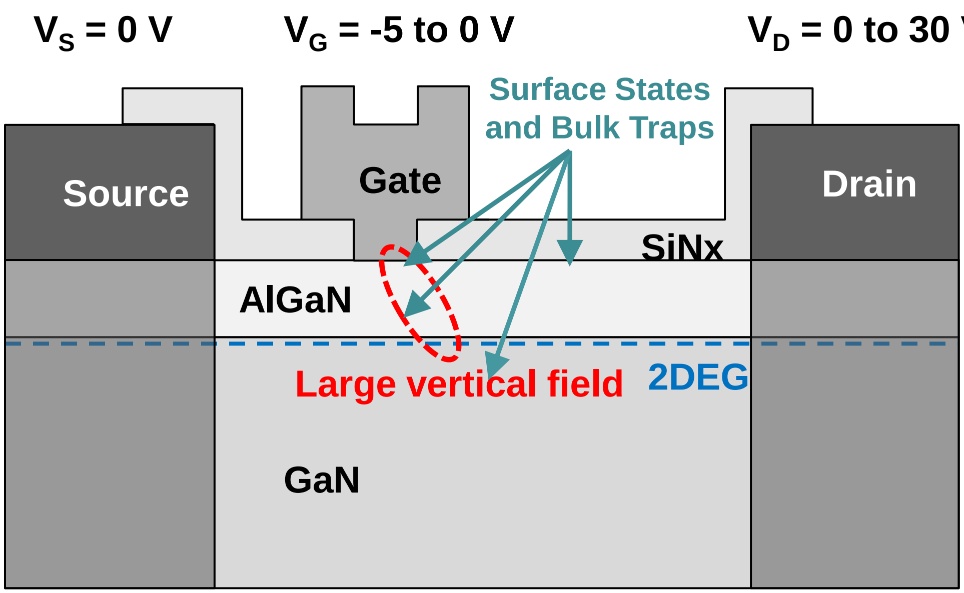
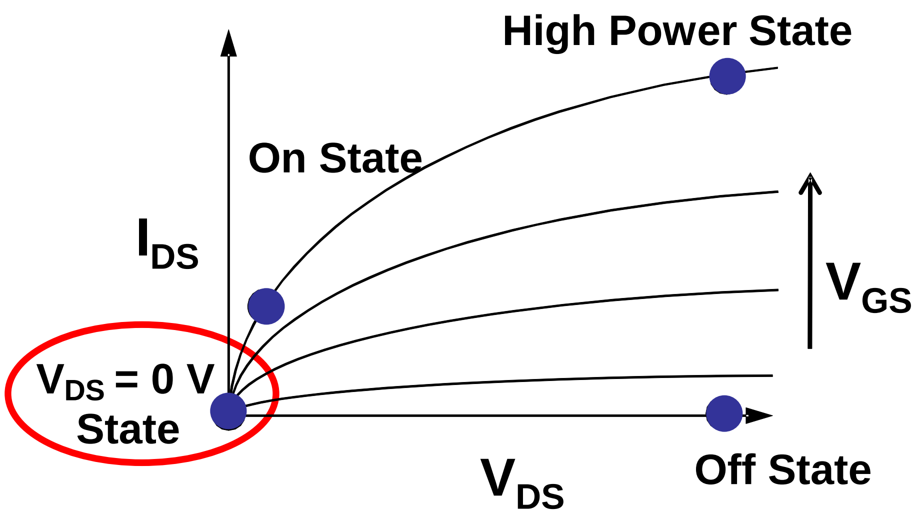
Mechanical Stress on GaN HEMT Reliability



Stress on GaN HEMT I_G Degradation





- Large vertical field can possibly generate traps and cause degradation.
- Investigate mechanical stress effect on gate leakage, at varying gate biase, at V_{DS}= 0V state (isolate effect of vertical field).

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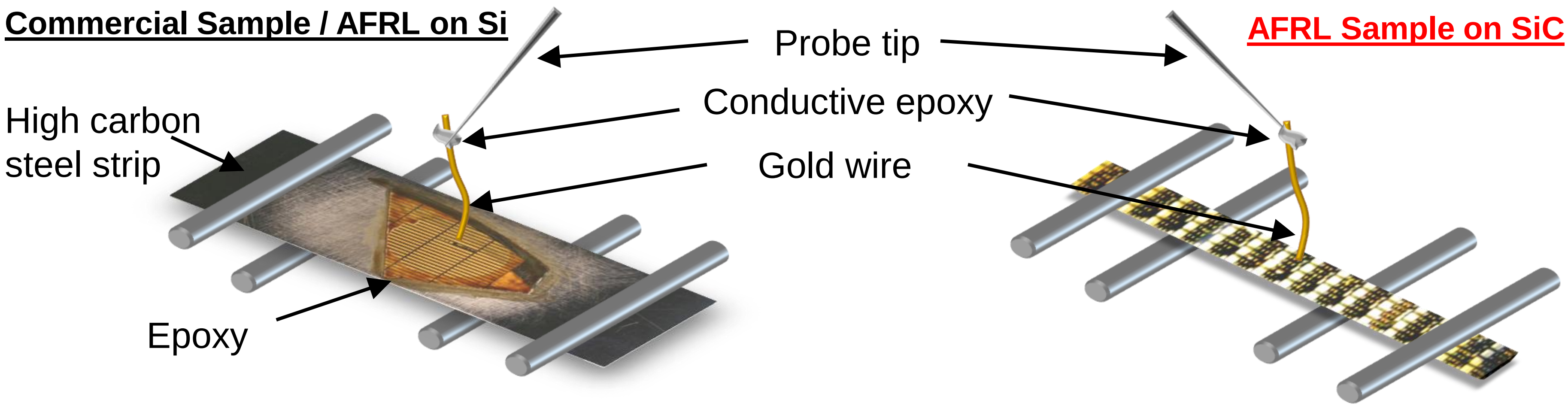
J_G Stress Dependence Measurement Technique

Stabilization

Bias device in dark at constant V_G → Wait until steady state →

Stressing

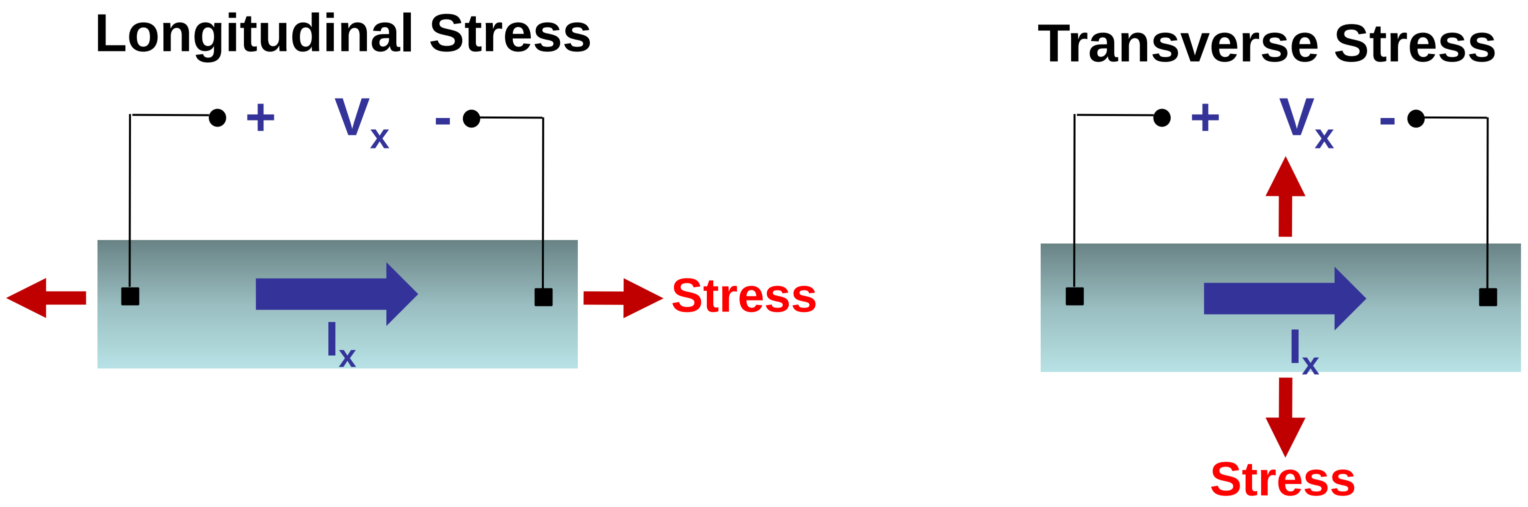
Incrementally apply stress & measure $\Delta J_G/J_G$



	Commercial on Si	AFRL on Si	AFRL on SiC
Young's Modulus GPa)	169	169	544
Sample Thickness (μm)	150	490	400

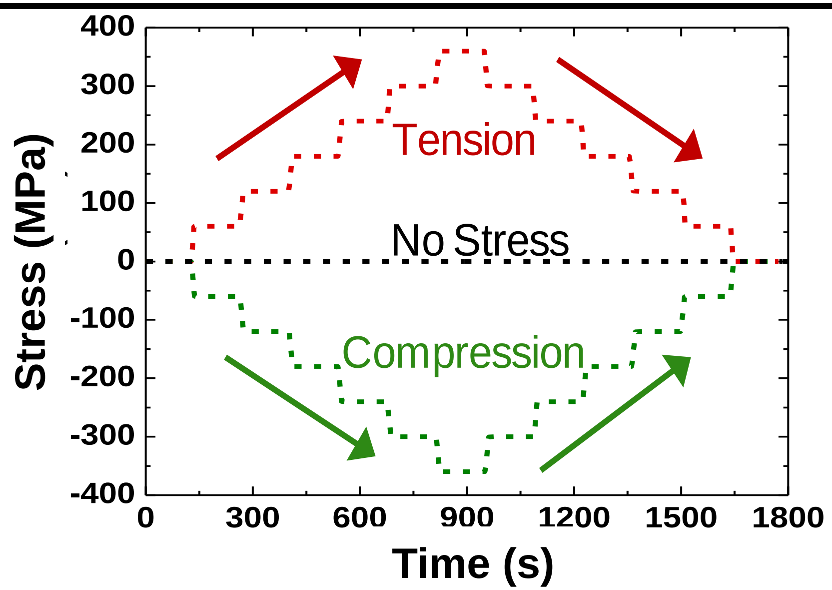
SiC substrate is more rigid than Si, need to bend SiC substrate directly

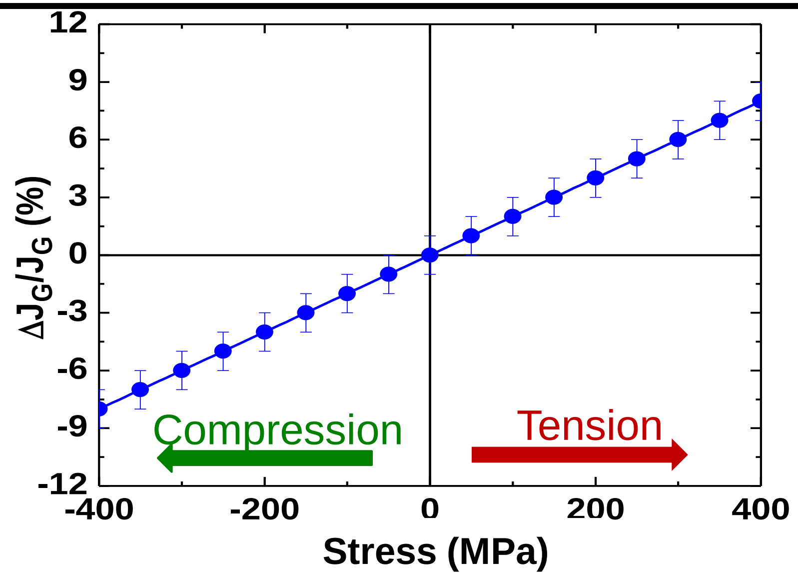
Longitudinal and Transverse Mechanical Stress



- GaN HEMT has biaxial tensile stress from lattice mismatch and inverse piezoelectric effect
- Investigate effect of uniaxial longitudinal and transverse stress on –
  - Commercial on Si
  - AFRL on SiC
  - AFRL on Si

J_G Stress Dependence Measurement Procedure





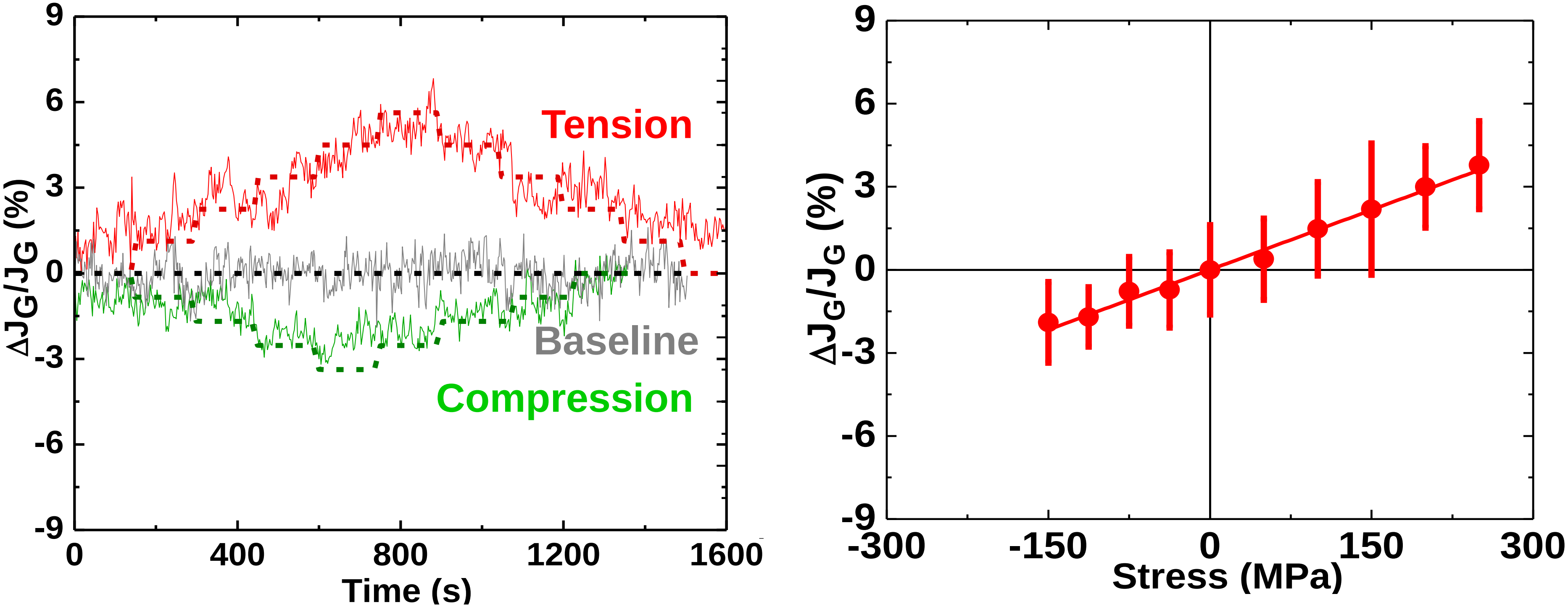
- Incrementally apply stress (tensile and compressive) and release it.
- Measure J_G at each stress point over the elapsed period of applied stress and take the average.

	Commercial on Si	AFRL on SiC	AFRL on Si
Longitudinal Stress	√	√	
Transverse Stress			√

J_G Longitudinal Stress Dependence: AFRL on SiC

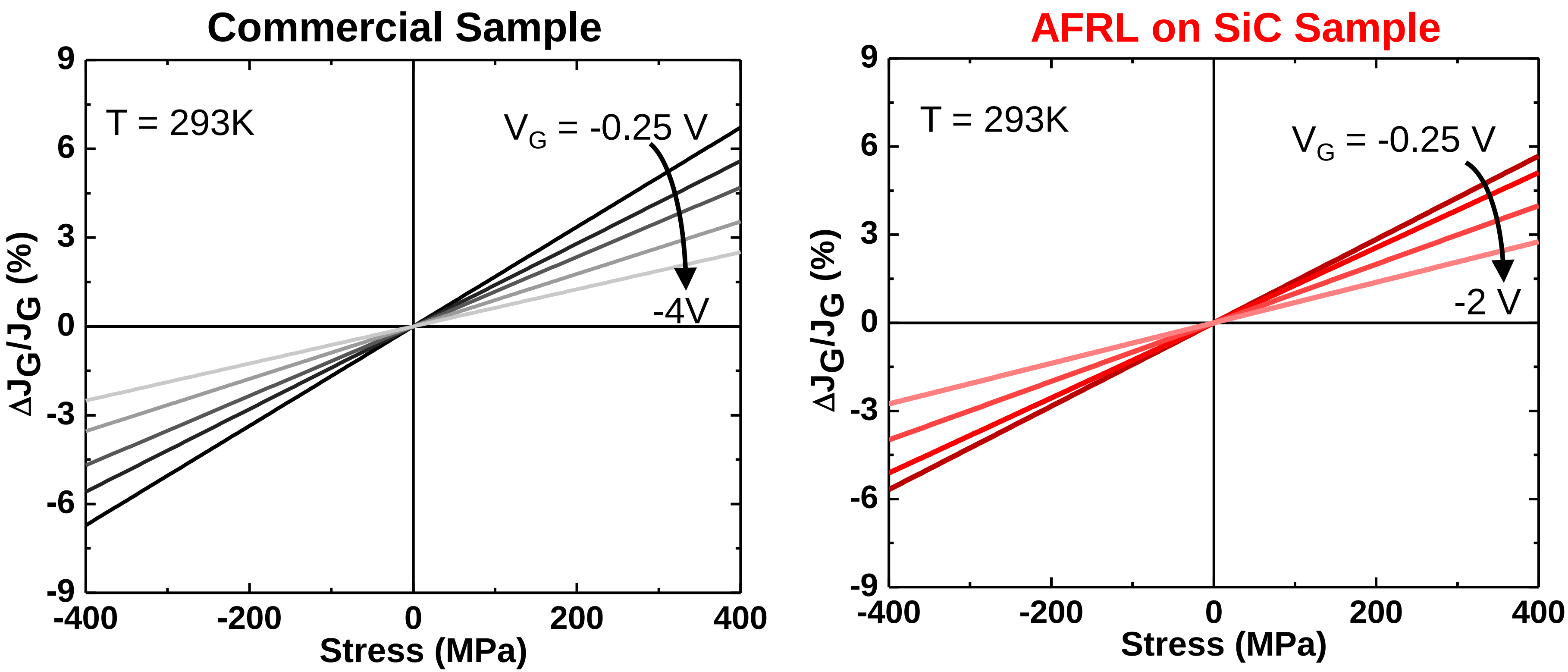
$V_{GS} = V_{GD} = -0.25$ V

T=293 K



- As Tension ↑ ΔJG ↑
- As Compression ↑ ΔJG ↓

Longitudinal Stress Effect : Commercial vs. AFRL

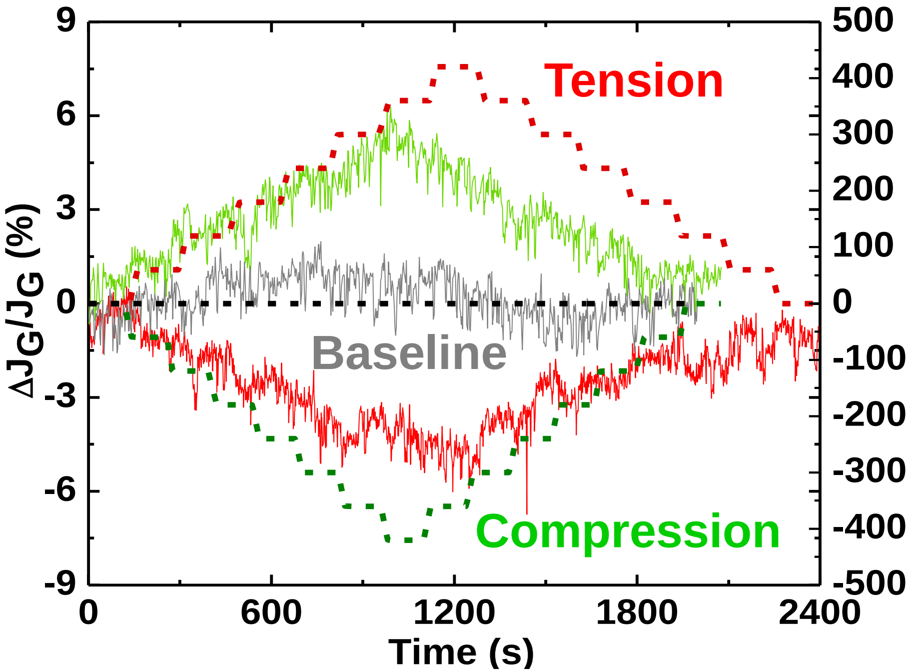


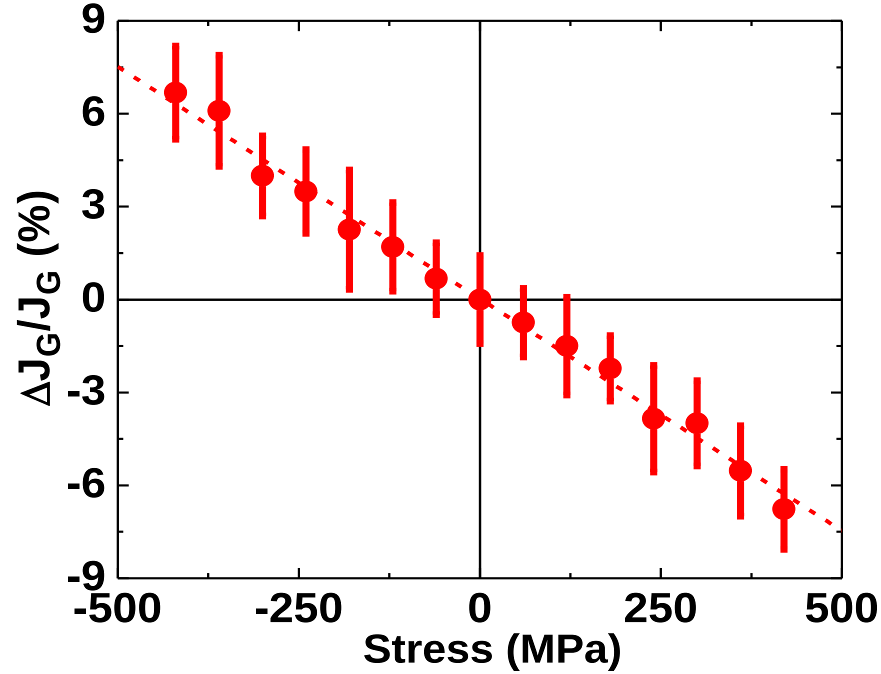
- Change in J_G with stress decreases with increase in reverse V_G.
- Possibly similar gate leakage mechanism in both samples.

J_G Transverse Stress Dependence: AFRL on Si

$V_{GS} = V_{GD} = -0.25$ V

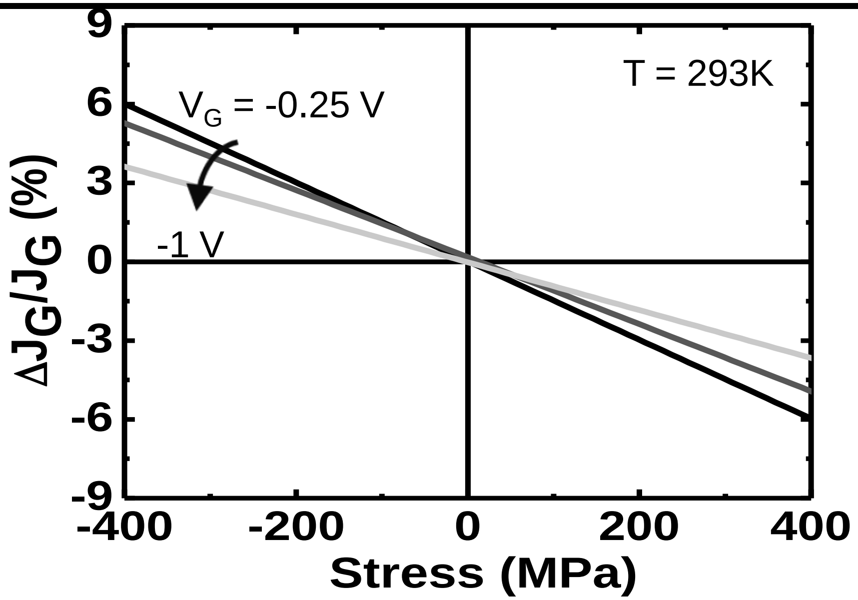
T=293 K





- **As Tension ↑ ΔJG ↓**
- **As Compression ↑ ΔJG ↑**

Transverse Stress Effect: AFRL on Si

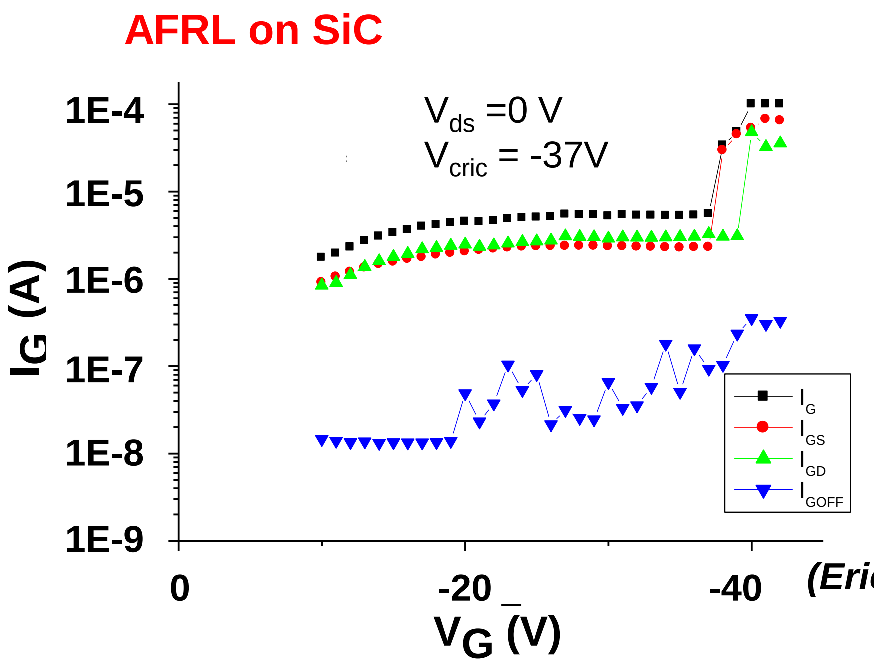


- Effect of transverse stress is opposite to longitudinal stress.
  - Combination of stress dependence of effective mass and trap energy
- Change in J_G with stress decreases with increase in reverse V_G .

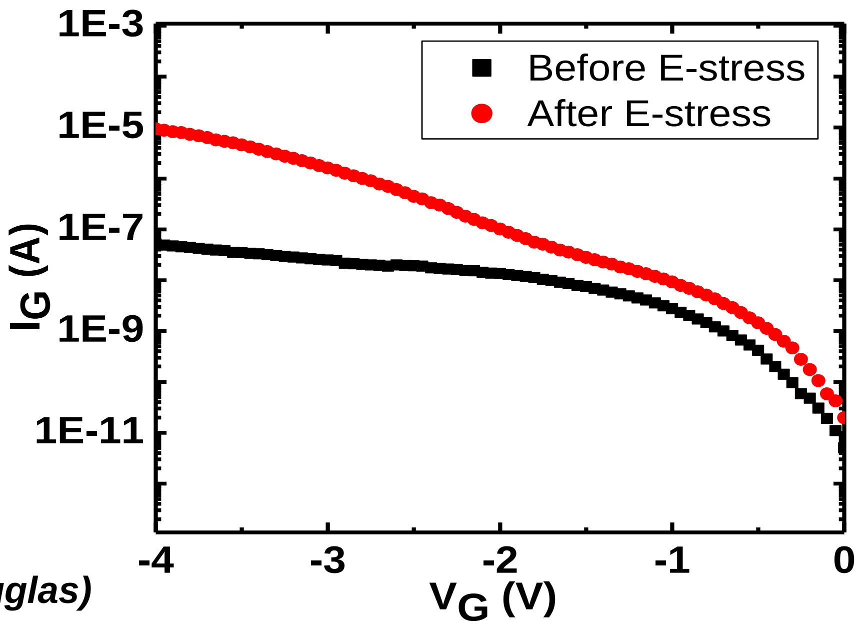
		Commercial on Si	AFRL on SiC	AFRL on Si
Longitudinal Stress	Tension	√	√	
	Compression	√	√	
Transverse Stress	Tension			√
	Compression			√

Combining Electrical and Mechanical Stress

- Collaborating with Erica (Dr. Pearton, Dr. Ren) to characterize effect of mechanical and electrical stress on (t > 0) degradation



(Erica Douglas)



- Gate current increase indicates degradation after electrical stress

Measuring D_{it} from Subthreshold Slope

D_{it}: Interface Trap density

Subthreshold slope of GaN HEMT:

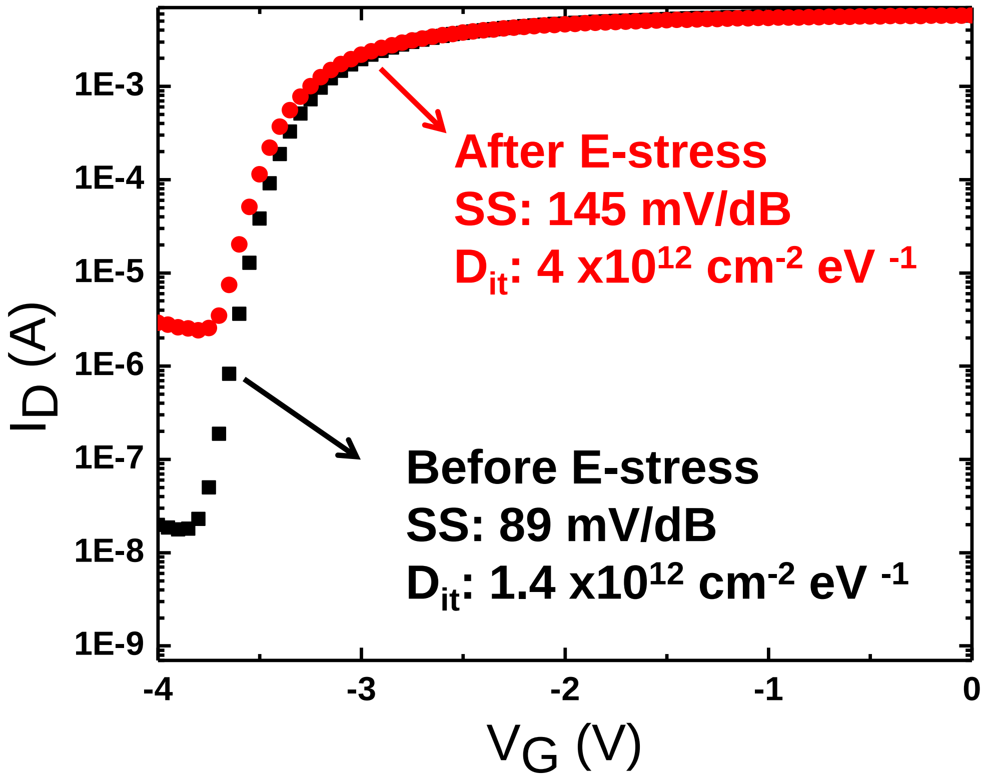
$$S \approx \frac{kT}{q} \ln 10 \cdot \left[1 + \frac{C_{it}}{C_{AlGaN}} \right]$$

(J.W. Chung *Proc. 65th Device Res. Conf. Dig.*, 2007)
(S.M. Sze, Physics of Semiconductor Devices, III edition, 2007)

- No depletion capacitance
- Quantum capacitance neglected

$$\boldsymbol{C_{it} = qD_{it}}$$

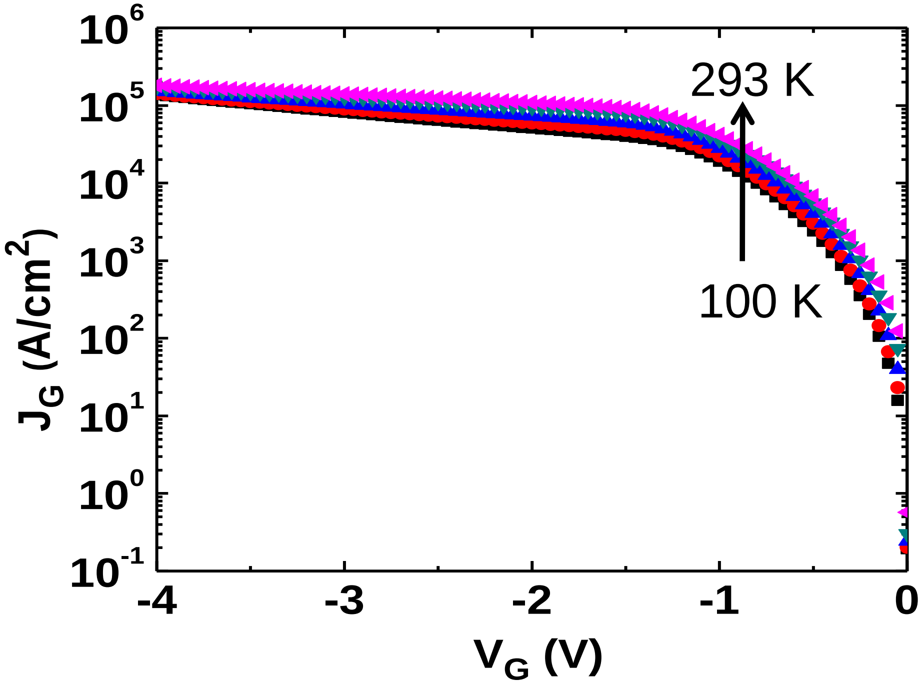
D_{it} Estimation in AFRL on SiC



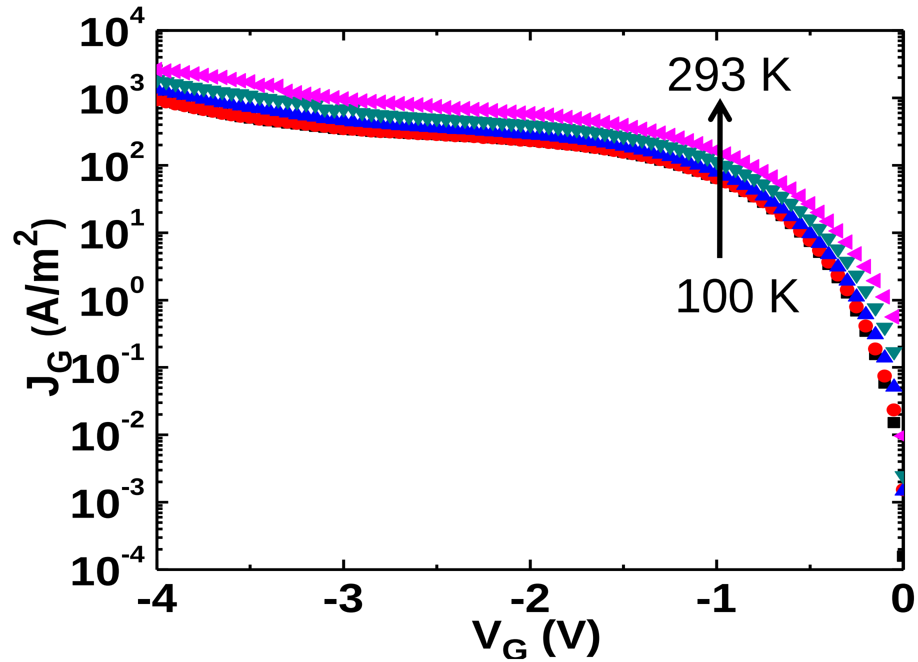
- Subthreshold slope (SS) increases after the electrical stress.
- Hence, interface trap density increases after the electrical stress.

J_G Temperature Dependence

Commercial Sample



AFRL on SiC



- Temperature dependence of J_G was measured to investigate gate leakage transport mechanisms

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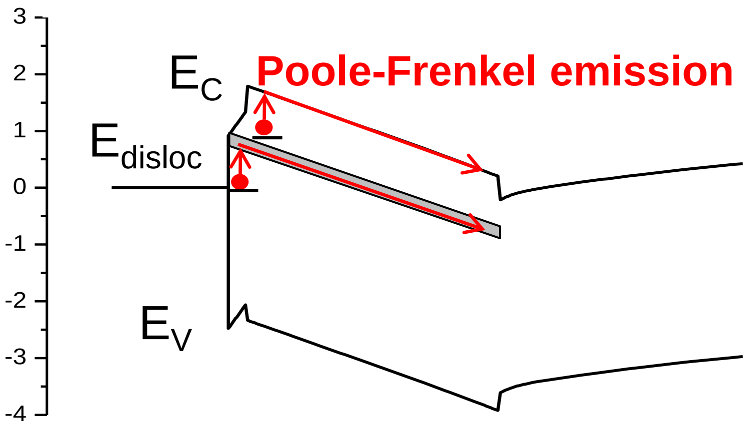
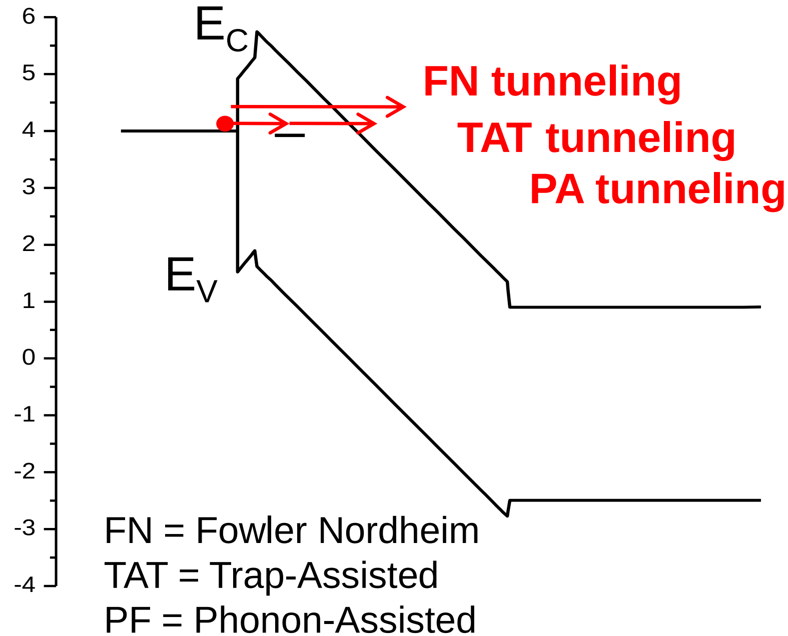
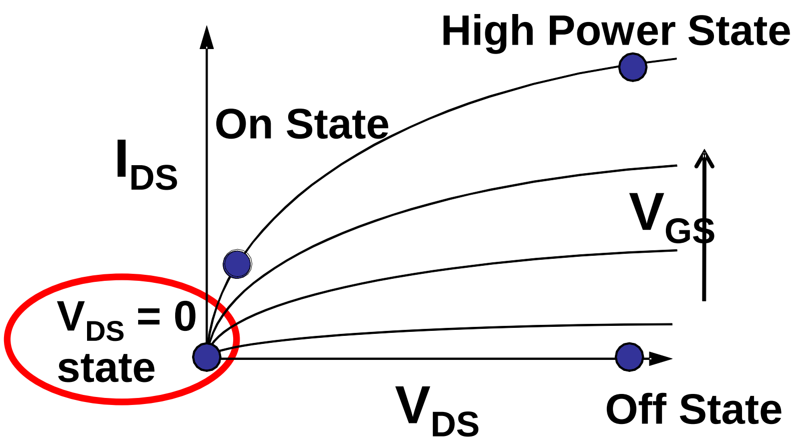
Possible Leakage Mechanisms

Low Reverse Bias



High Reverse Bias (-4 V)

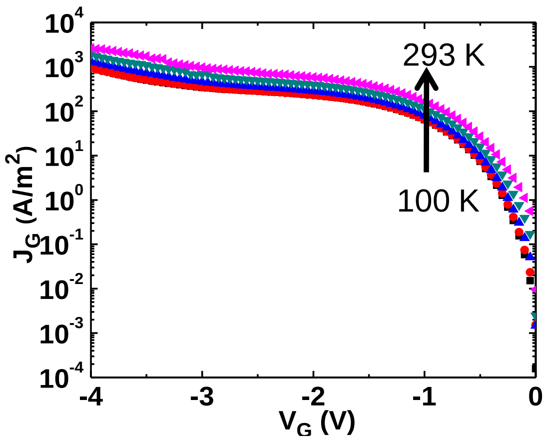


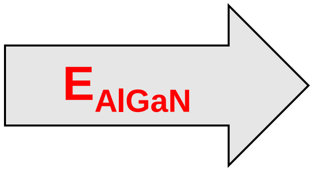


Dominant leakage mechanism depends on bias

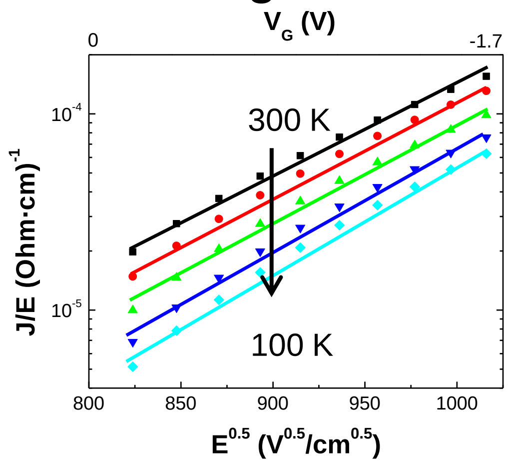
Need for E_{AlGaN} Calculation

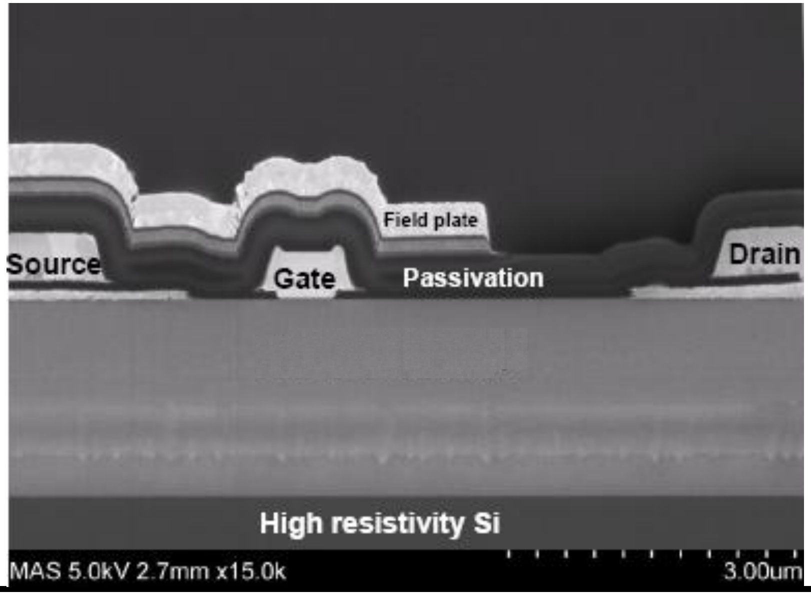
Measured I_G-V_G

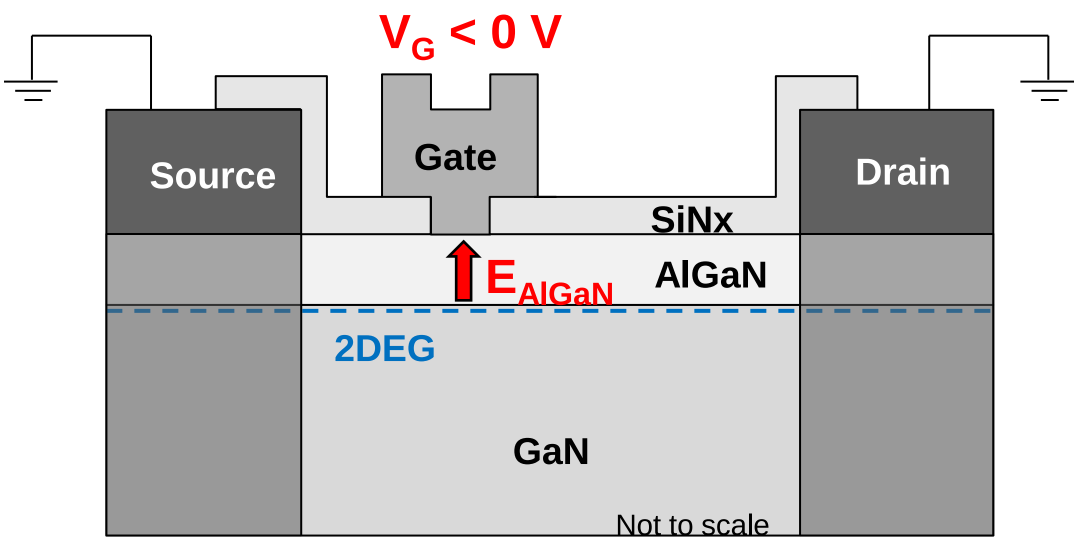




Leakage Model

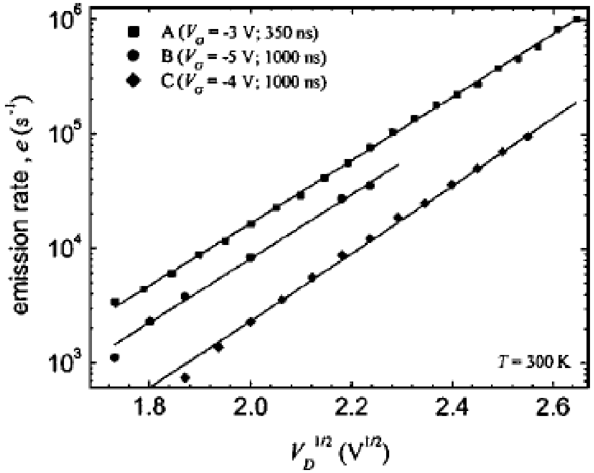




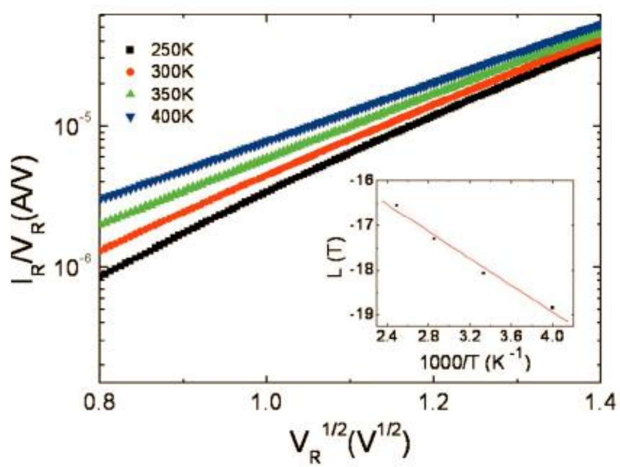


Models in Literature

Used Applied Voltage

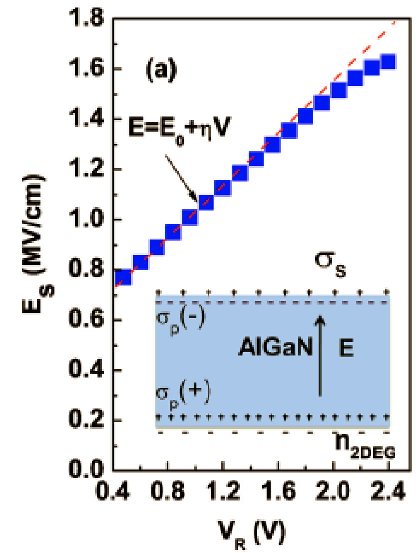


Mitrofanov and Manfra, JAP 2004.



Chikhaoui, *et al*. APL 2010.

Measured E_{AlGaN}



Yan, *et al*. APL 2010.

2D E_{AlGaN} Simulation

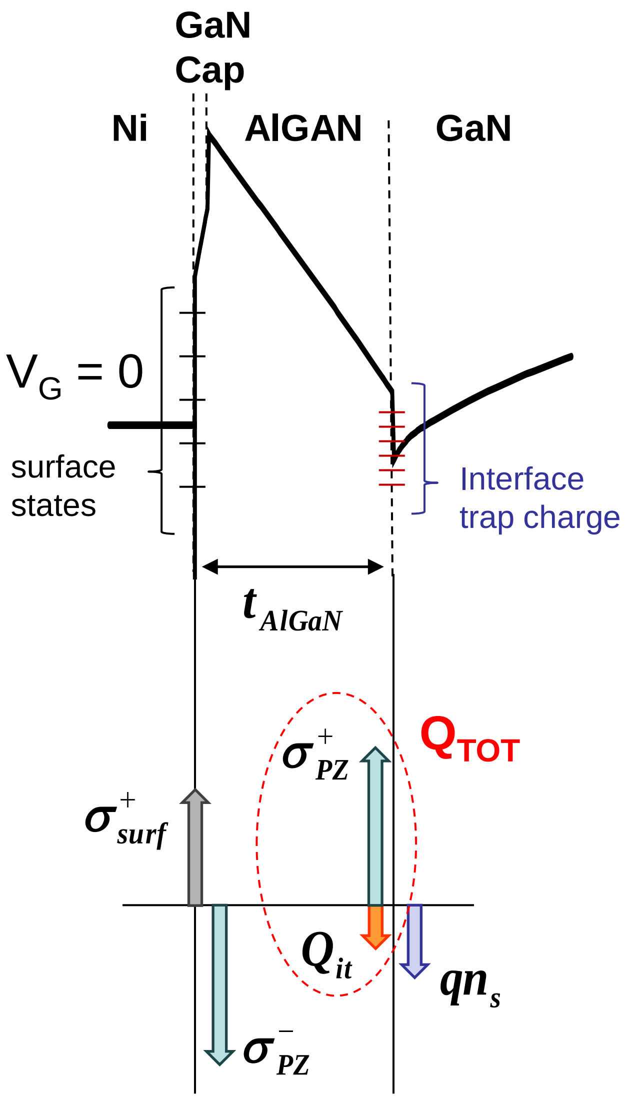
V_{GS} (V)	Electric field component	Electric field (MV/cm) SB-HFET	EB-HFET
0	vertical	−1.06	−0.90
0	lateral	−0.12	−2.45
−6	vertical	−2.05	−0.90
−6	lateral	−1.75	−2.45

Miller, Dang, and Yu, JAP 2000.

Objective:

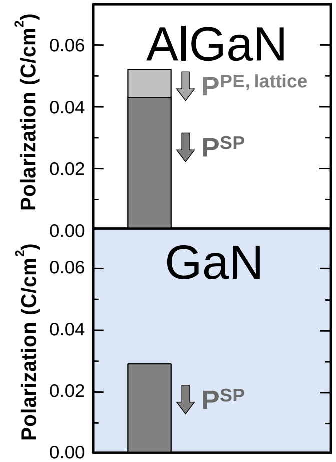
- Accurately determine E_{AlGaN} to compare measurements to leakage transport models

Device Physics: 2DEG Formation



- GaN HEMT polarization:

$$\sigma_{PZ} = \left(P^{SP}_{AlGaN} + P^{PE}_{AlGaN}\right) - P^{SP}_{GaN}$$



Koehler, et al., EDL 2010

- Surface states populate interface charge and 2DEG Ibbetson's "surface donor model"

$$\sigma^+_{surf} + Q_{it} + qn_s = 0$$

Ibbetson, et al., APL 2000.

- 2DEG depends on total charge (Q_{TOT}) at interface:

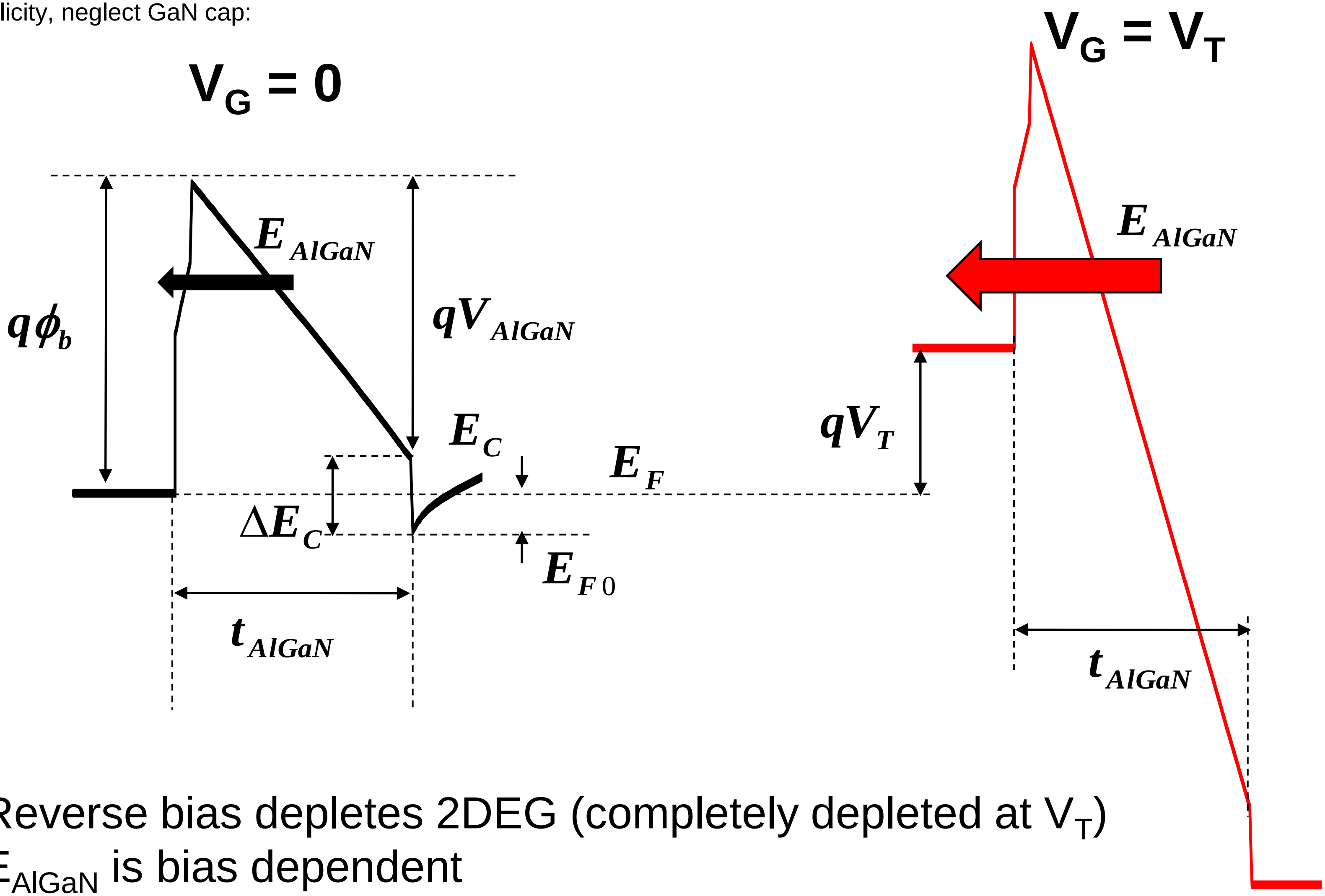
$$n_s \propto Q_{TOT}$$

$$Q_{TOT} = \sigma_{PZ} - Q_{it}$$

Q_{TOT} needed for E_{AlGaN} calculation

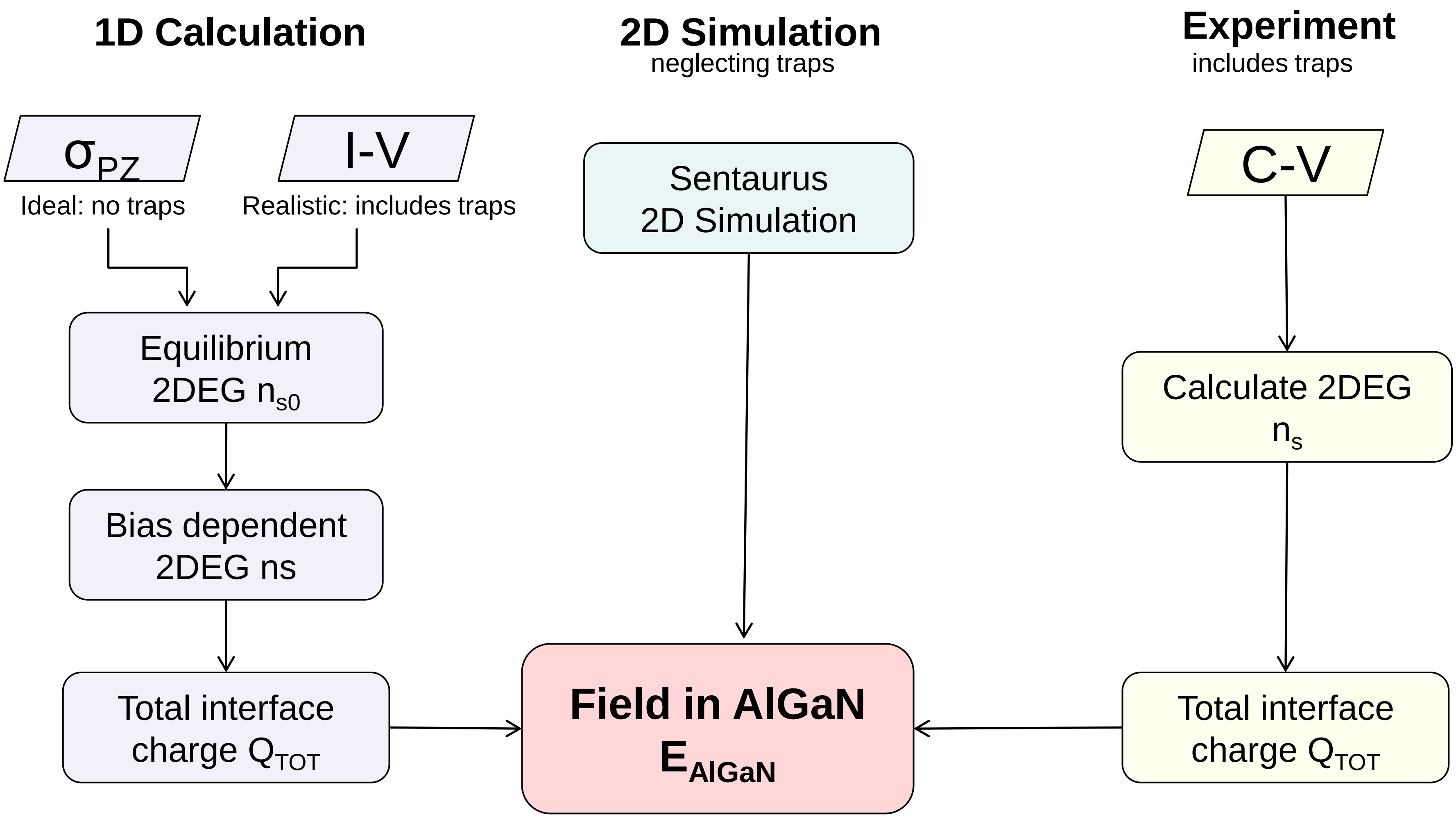
E_{AlGaN} at $V_{DS} = 0$

For simplicity, neglect GaN cap:



- Reverse bias depletes 2DEG (completely depleted at V_T)
- E_{AlGaN} is bias dependent

E_{AlGaN} Analytical Procedure



- **Compare 1D, 2D and Experimental E_{AlGaN}**

1D Model Details

Ideal: no traps | **Realistic: includes traps**

σ_{PZ} → $Q_{TOT} = \sigma_{PZ}$ → Equilibrium 2DEG n_{s0}

I-V → experimental V_T → Equilibrium 2DEG n_{s0}

$$n_{s0} = \frac{Q_{TOT}}{q} - \frac{C_{AlGaN}}{q^2}\left[q\phi_b + E_{F0} - \Delta E_C\right]$$

Ambacher, et al., JAP 1999.

$$n_{s0} = \frac{-C_{AlGaN} V_T}{q}$$

Equilibrium 2DEG n_{s0} ↓

Bias dependent 2DEG n_s

$$n_s = n_{s0} + \left(\frac{C_{AlGaN}}{q}\right) V_G$$

$$n_s = n_{s0} + \left(\frac{C_{AlGaN}}{q}\right) V_G$$

↓

Total interface charge Q_{TOT}

$$Q_{TOT} = \sigma_{PZ}$$

$$Q_{TOT} = q n_{s0} + \frac{C_{AlGaN}}{q}\left[q\phi_b + E_{F0} - \Delta E_C\right]$$

↓

Field in AlGaN E_{AlGaN}

$$E_{AlGaN} = \frac{Q_{TOT} - q n_s}{\varepsilon_{AlGaN}}$$

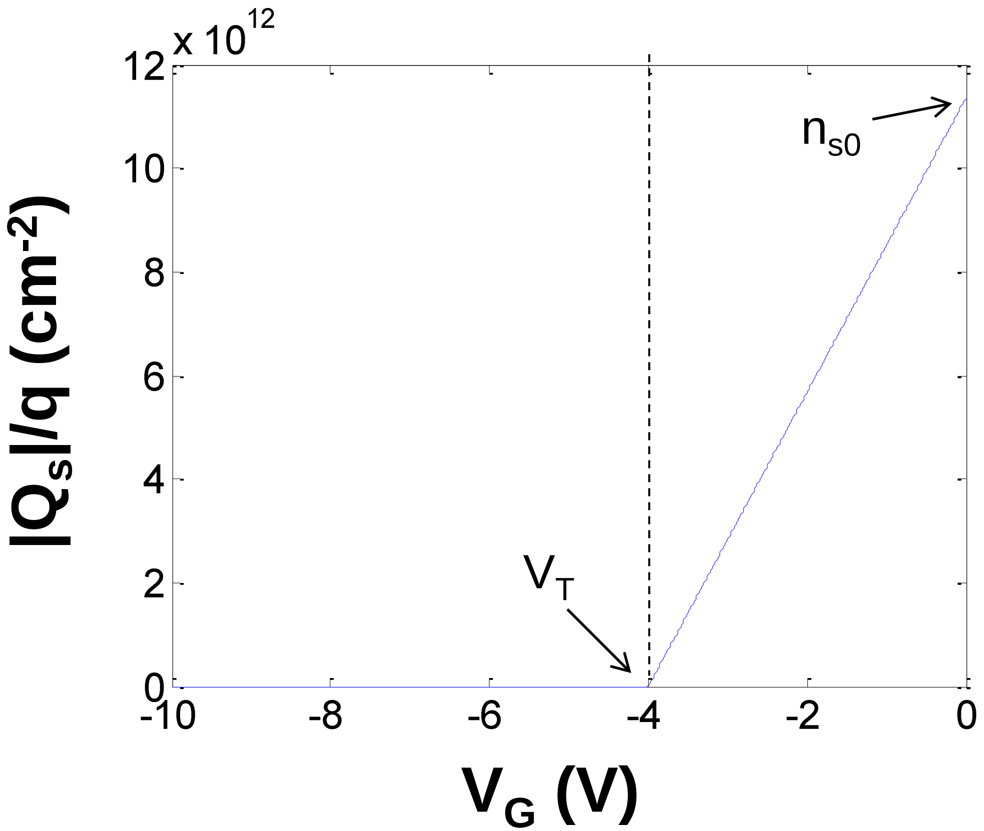
Bias Dependence of 2DEG

Above V_T:

$$n_s = n_{s0} + \left(\frac{C_{AlGaN}}{q}\right) V_G$$

Below V_T:

$$n_s = 0$$



- 2DEG decreases linearly until V_T
- V_T is defined when 2DEG is completely depleted
- Charge density at surface ≈ zero below V_T (no holes to accumulate $n_i \sim 1 \times 10^{-10}$)

1D Calculation of E_{AlGaN} for Ideal HEMT

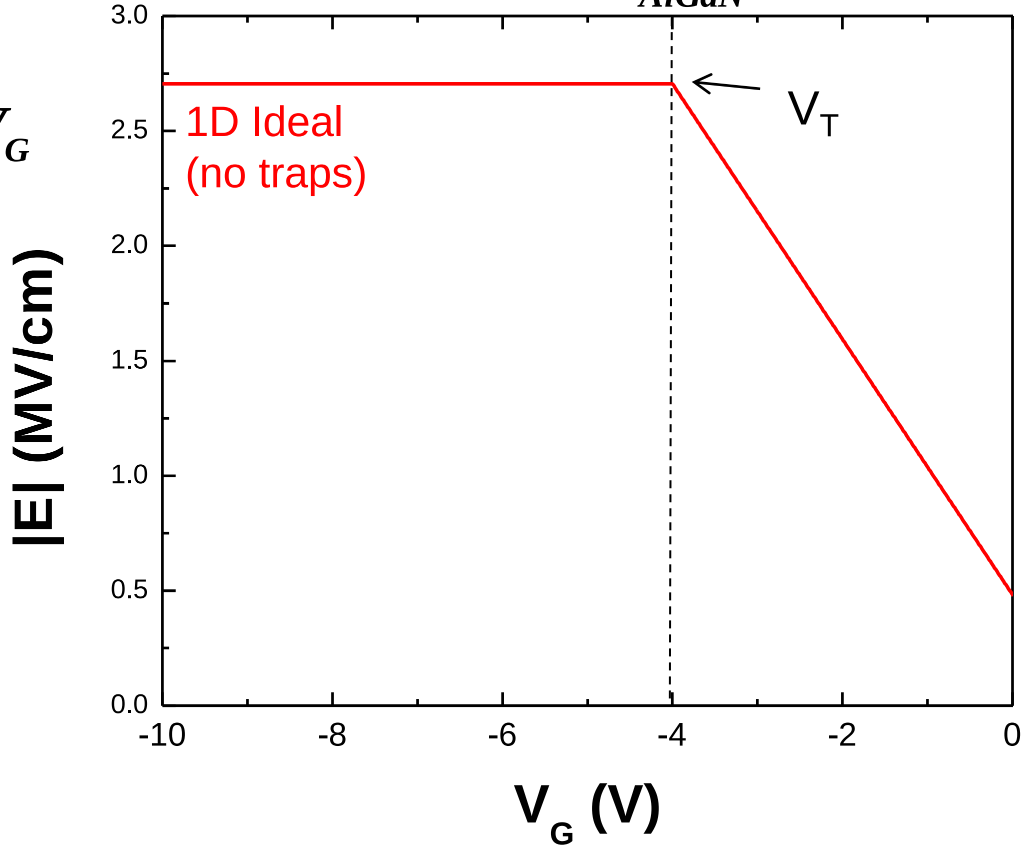
$$E_{AlGaN} = \frac{Q_{TOT} - qn_s}{\varepsilon_{AlGaN}}$$

Above V_T:

$$n_s = n_{s0} + \left(\frac{C_{AlGaN}}{q}\right)V_G$$

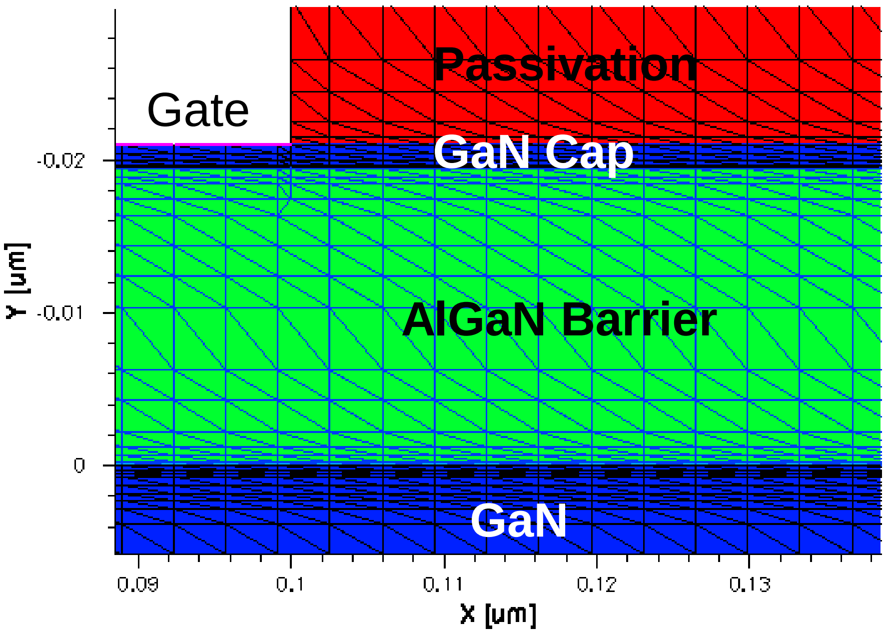
Below V_T:

$$n_s = 0$$



- E_{AlGaN} saturates below V_T

2D Sentaurus Simulation of E_{AlGaN}



Poisson's Equation:

$$\varepsilon\nabla^2\Psi = -q(p - n + N_d - N_a)$$

Electron Continuity:

$$\nabla \vec{J}_n = q\frac{\partial n}{\partial t} = qn\mu_n\nabla\Psi + qD_n\nabla n$$

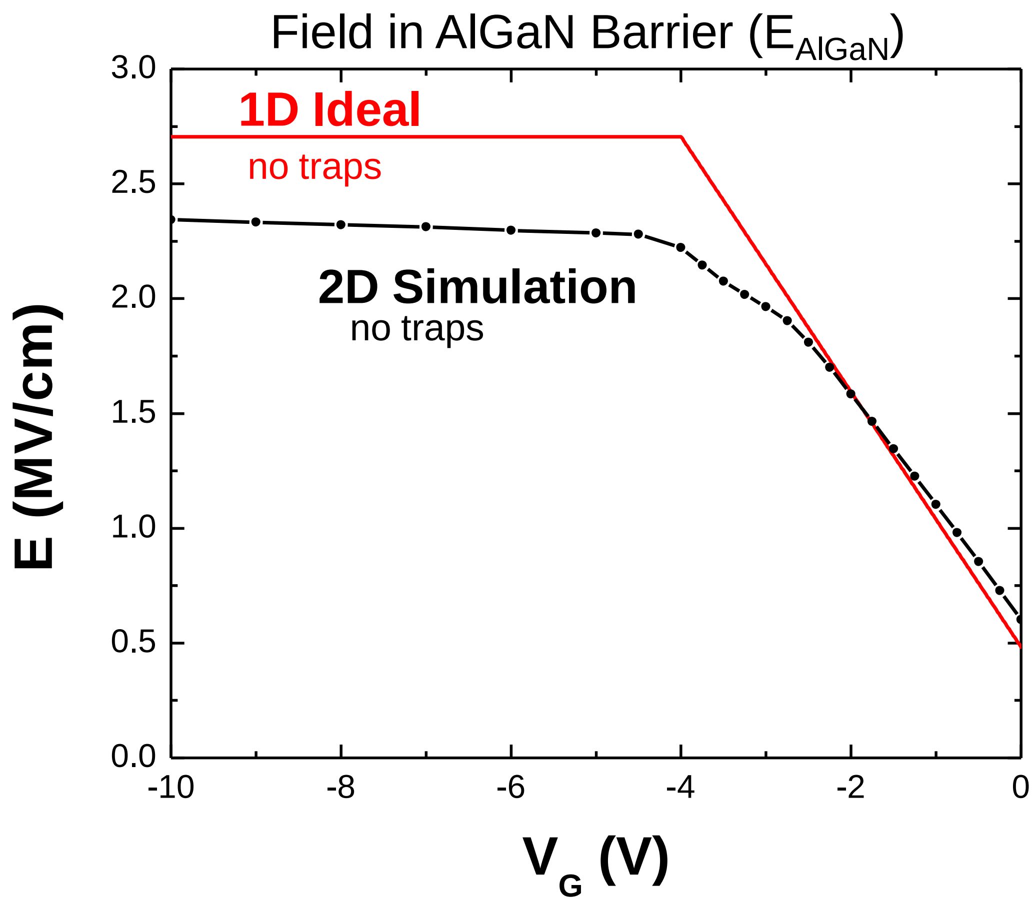
Hole Continuity:

$$\nabla \vec{J}_p = q\frac{\partial n}{\partial t} = qn\mu_p\nabla\Psi + qD_p\nabla p$$

* Used same constants as 1D calculation

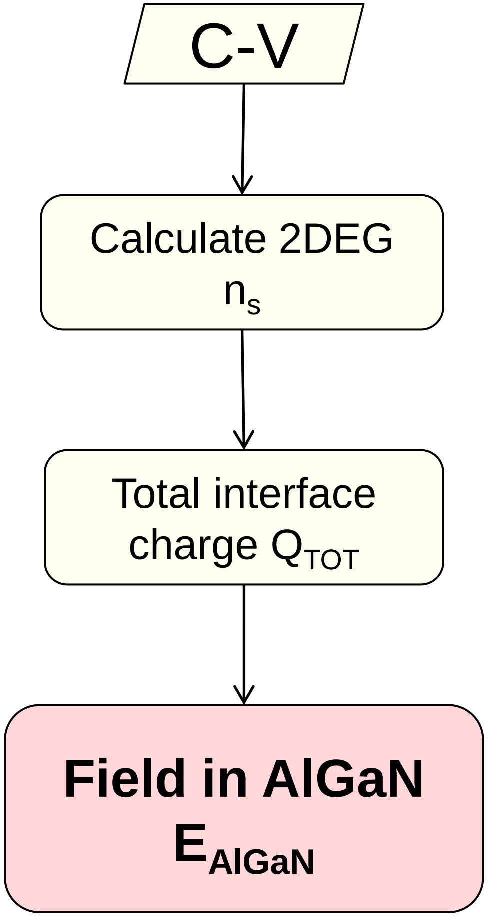
- **Piezoelectricity:** Piezoelectric polarization and spontaneous polarization are implemented using fixed interface charge at the interfaces
- **Mobility:** Doping dependence, high field saturation, temperature
- **SRH:** Recombination/generation

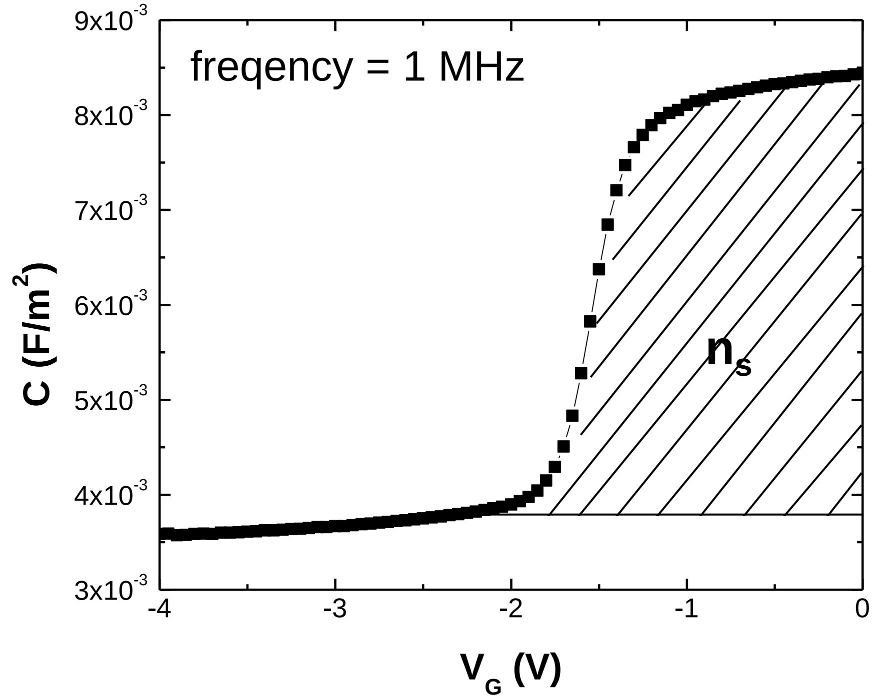
Comparing 1D to 2D Simulation



- 2D simulation also shows saturation of E_{AlGaN} below V_T

E_{AlGaN} from Experiment

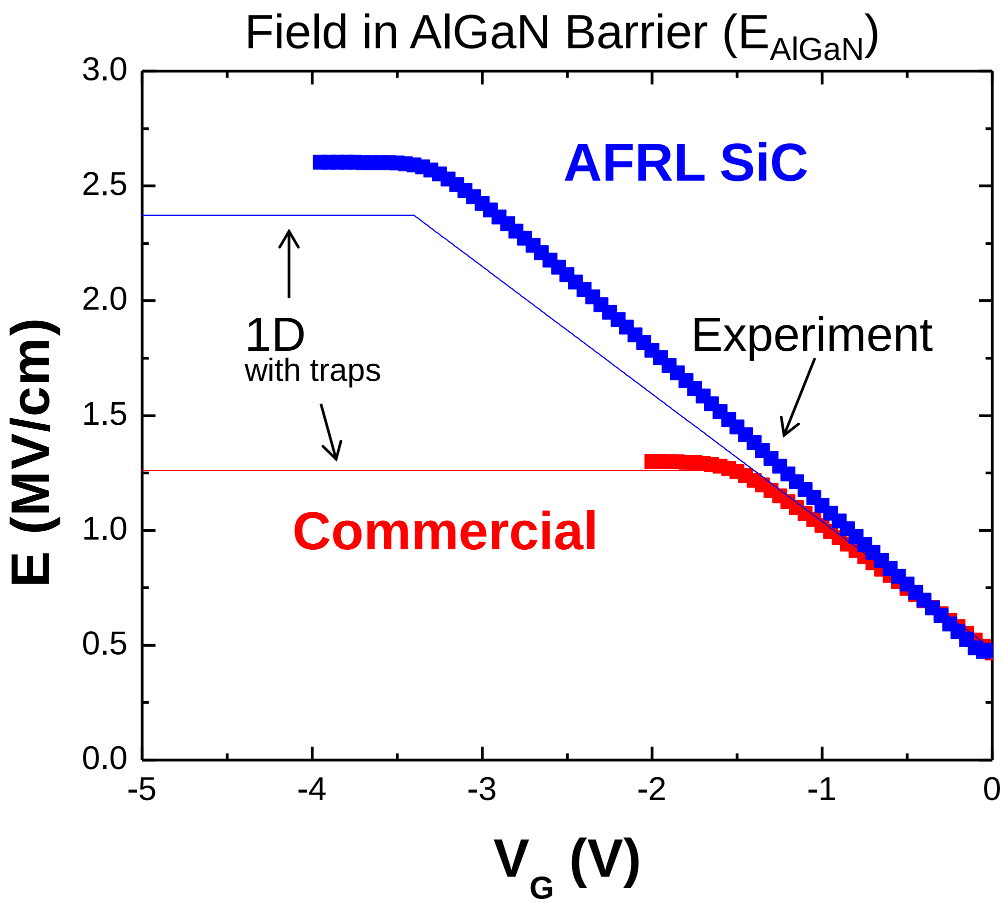




$$E_{AlGaN} = \frac{Q_{TOT} - qn_s}{\varepsilon_{AlGaN}}$$

- Direct measurement of n_s to calculate E_{AlGaN} in real device

1D Model (with traps) vs. Experiment



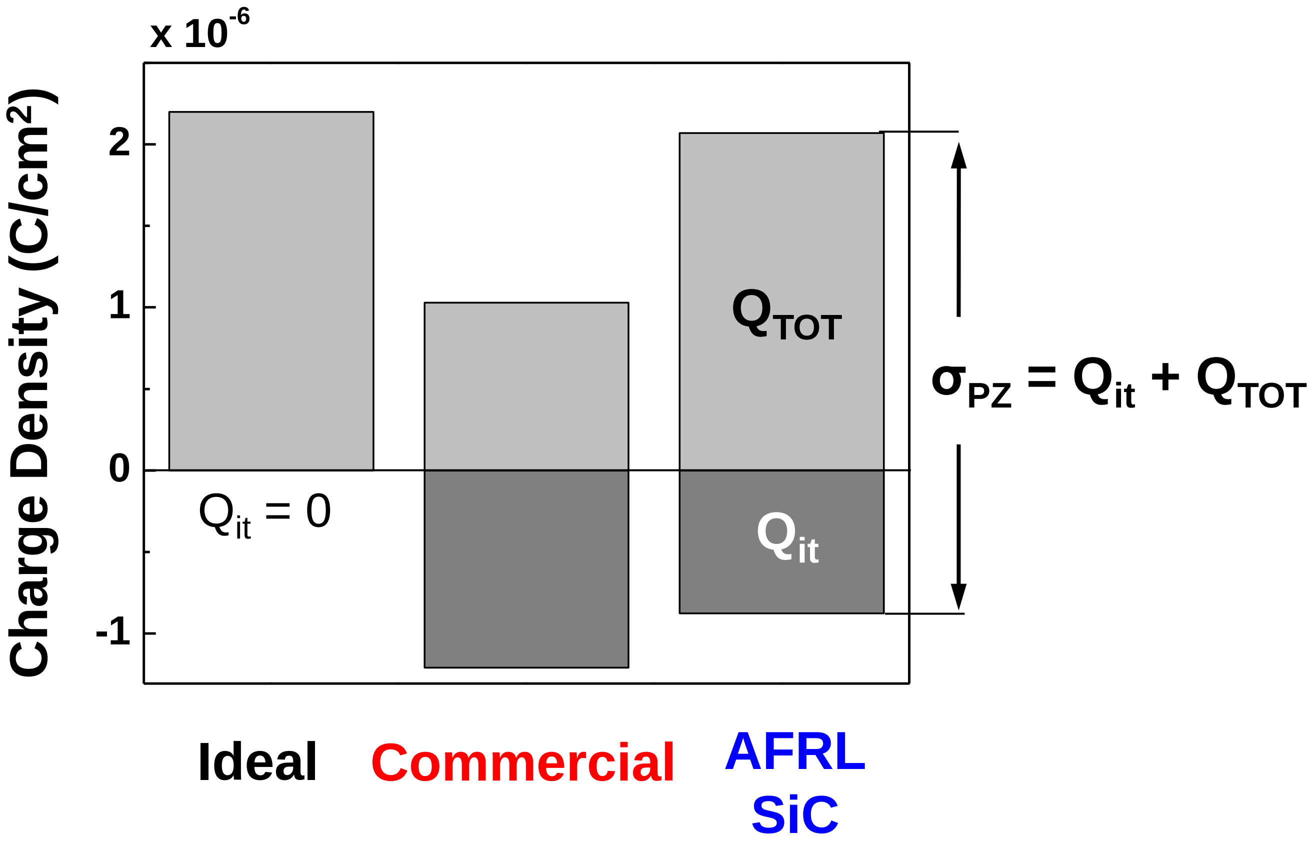
- 1D model with traps captures physics of real device
- V_T and saturation level of E_{AlGaN} is different between AFRL and Commercial (difference in number of traps)

Commercial vs. AFRL Comparison

Calculated from V_T

Estimated from SS (assuming all traps filled)

$$Q_{TOT} = \sigma_{PZ} - Q_{it}$$

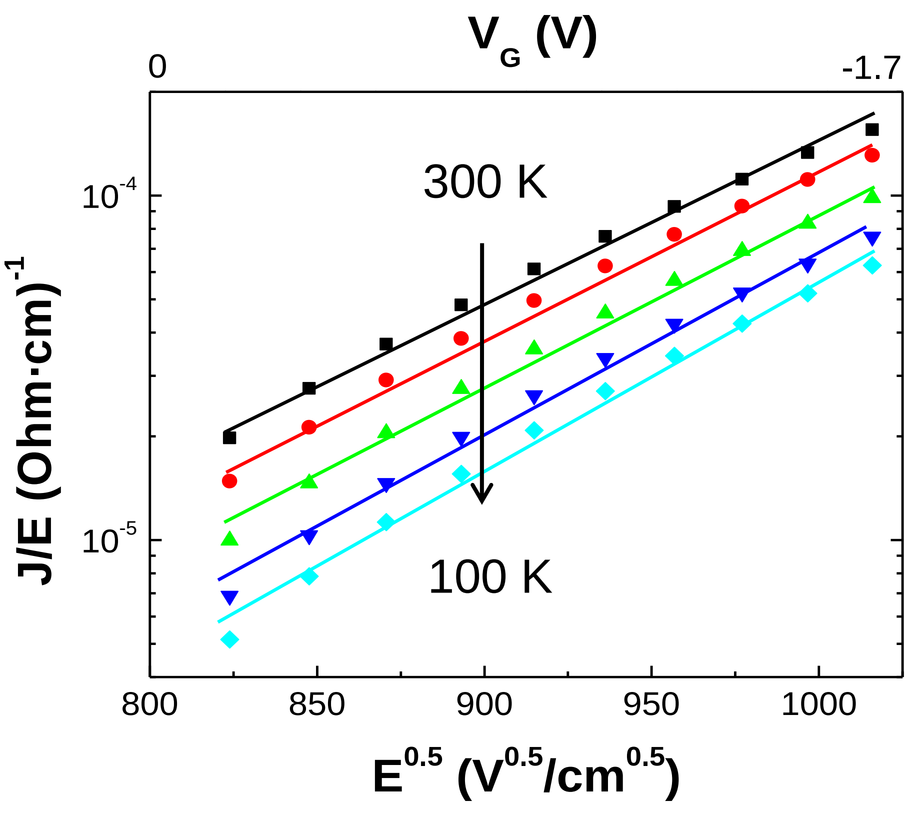


- AFRL SiC has larger Q_{TOT} and less Q_{it} than Commercial device

Characterizing Trap Levels

Measured E_{AlGaN} used to understand tunneling mechanism

Poole-Frenkel dominant at low field



Poole-Frenkel Model:

$$J = CE_{AlGaN} \exp\left[-\frac{q\left(\phi_t - \sqrt{qE_{AlGaN} / \pi\varepsilon_0\varepsilon_s}\right)}{kT} \right]$$

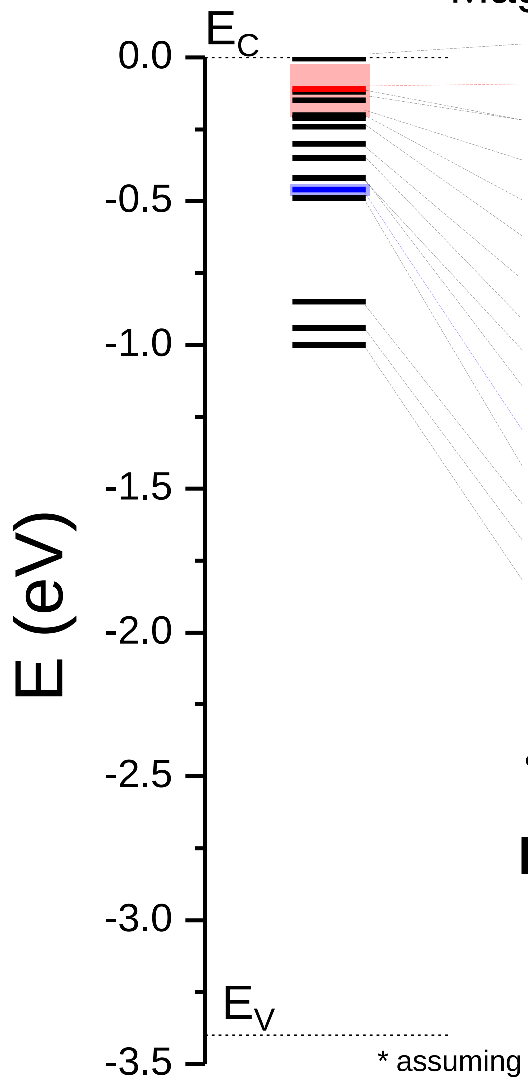
$$\equiv m(T)\sqrt{E_{AlGaN}} + b(T)$$

Can estimate trap level using E_{AlGaN}

AFRL SiC:	$\phi_t = 0.46 \pm 0.01$ eV
Nitronex:	$\phi_t = 0.11 \pm 0.09$ eV

*extracted at 250 and 300 K

Extracted Trap Energy Compared to Literature



- Shaded bands show measurement error

Extracted trap energies lie within published range

Change in Trap Energy with Mechanical Stress

$\Delta\phi_t(\sigma)$ is extracted at room temperature at 2 stress values:

$$\Delta\phi_t = \frac{-kT\log\left(\frac{\Delta J_G}{J_{G1}}+1\right)}{q}$$

- Stress changes φ_t only, not E_{AlGaN} (stress AlGaN = stress GaN)
- Can estimate stress dependence of φ_t from stress dependence of J_G

- Trap energy of both devices affected similarly with applied mechanical stress

AFRL SiC: $\Delta\phi_t = -3.8\ \mathrm{meV/GPa}$

Nitronex: $\Delta\phi_t = -3.2\ \mathrm{meV/GPa}$

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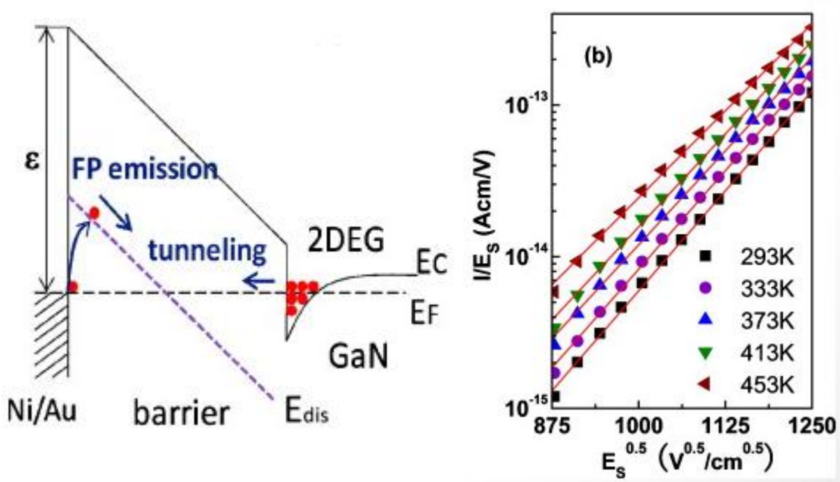
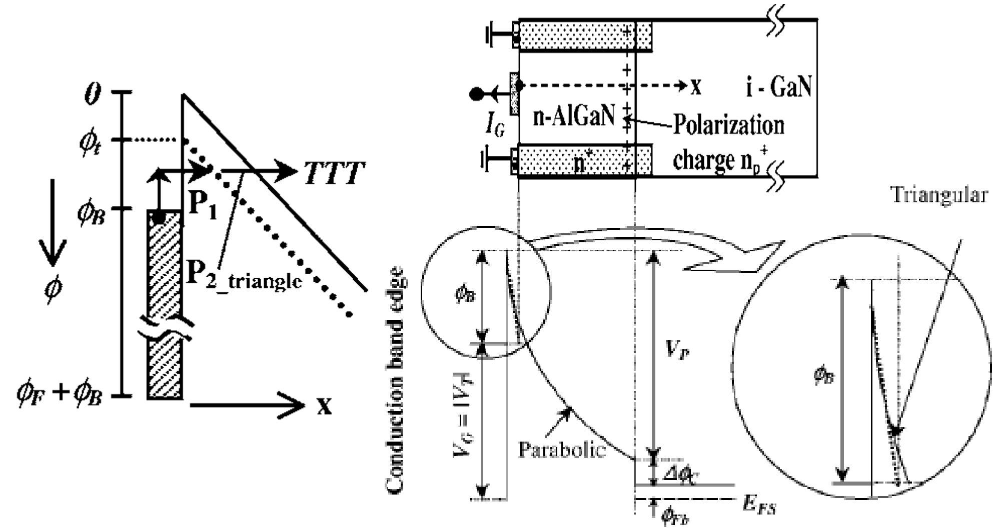
Literature Review on Gate Leakage

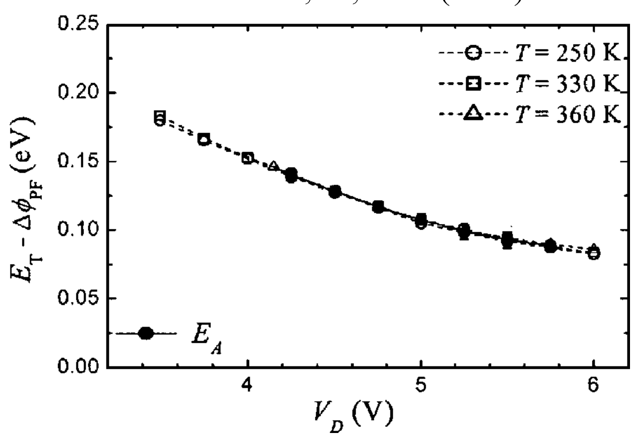
Yan et al. APL, 97, 153503 (2010)



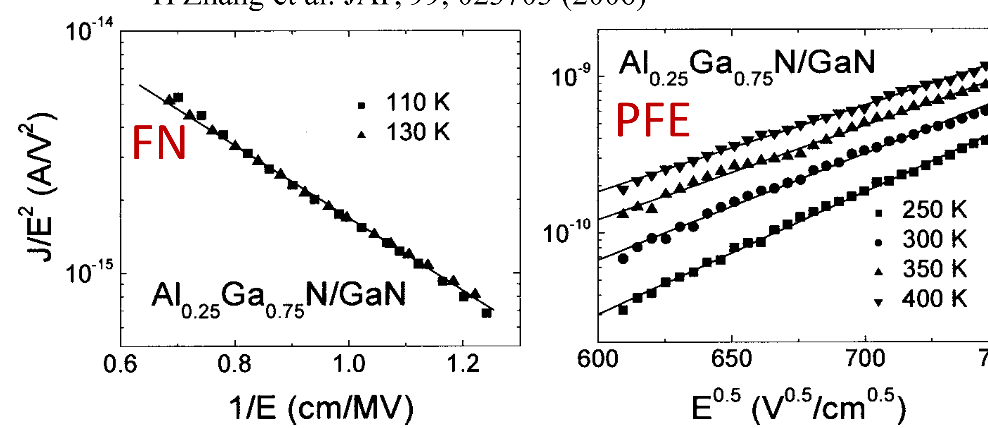
Sathaiya et al. JAP, 99, 093701 (2006)



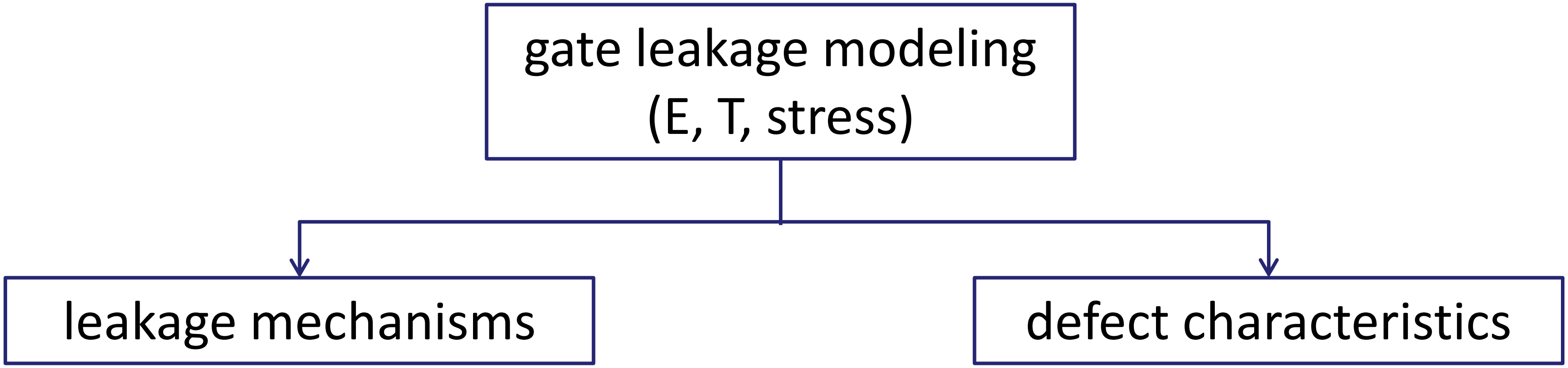
Mitrofanov et al. JAP, 95, 6414 (2004)



H Zhang et al. JAP, 99, 023703 (2006)



Simulation Overview



(Matlab coding)

- **Low reverse bias**
  Poole-Frenkel Emission
- **High reverse bias**
  Trap-assisted tunneling
  Phonon-assisted tunneling
  FN tunneling

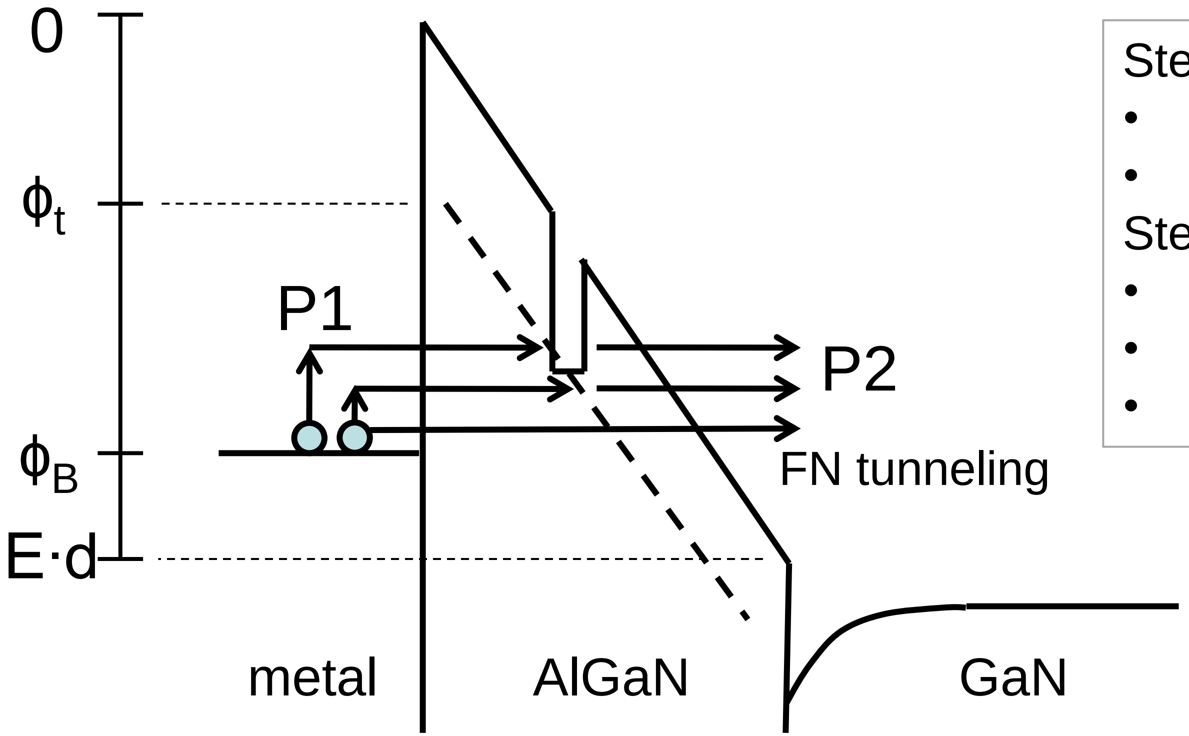
(DFT calculation using VASP)

Calculate for defect levels with and without stress

Targeted defects:

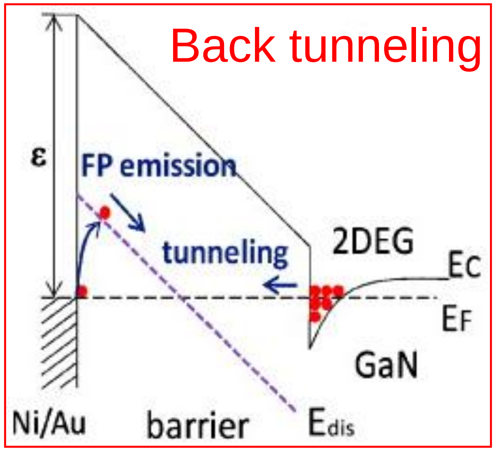
1) Ga and N vacancies
2) O substitute N

Gate Leakage Mechanisms



Step 1:
- Direct tunneling
- Thermal assisted tunneling

Step 2:
- Direct tunneling
- Phonon assisted tunneling
- Poole-Frenkel emission



- Assume uniform trap concentration
- Assume triangular potential within AlGaN
- Only one defect level is considered

DM Sathaiya et al. JAP, 99, 093701 (2006)

Leakage Simulation Details

- **FN tunneling:**

$$J = \frac{q^2 \left(m_0 / m_n^*\right)}{8\pi h \phi_b} E^2 \exp\left(-\frac{8\pi\sqrt{2m_n^*\left(q\phi_b\right)^3}}{3qhE}\right)$$

H Zhang et al. JAP, 99, 023703 (2006)

- **Trap-assisted tunneling:**

$$R_1 = C_1 N_t f_{FD}\left(1 - f\right) P_1$$

$$R_2 = C_2 N_t f \, P_2$$

R: tunneling/emission rate
P: tunneling/emission probability
f: probability of trap occupation

At steady state:

$$R_1 = R_2 \quad \Rightarrow \quad C_1 N_t f_{FD}\left(1 - f\right) P_1 = C_2 N_t f \, P_2 \quad \Rightarrow \quad f = \frac{C_1 f_{FD} P_1}{C_1 f_{FD} P_1 + C_2 P_2}$$

$$\Rightarrow \quad R = \frac{C_1 C_2 N_t f_{FD} P_1 P_2}{C_1 f_{FD} P_1 + C_2 P_2} = N_t \cdot \left(\frac{1}{C_1 f_{FD} P_1} + \frac{1}{C_2 P_2}\right)^{-1}$$

Overall leakage current density: $J = \frac{q}{E}\int_{\phi_t}^{E \cdot d} R\left(\phi\right) d\phi$

Two Step Tunneling Model

Step 1 (thermal assisted direct tunneling):

$$f_{FD} = \frac{1}{1+\exp\left[q\left(\phi_B - \phi\right)/kT\right]}$$

$$P_1 = \exp\left[-\frac{8\pi\sqrt{2m_{AlGaN}q}}{3hE}\left(\phi^{3/2} - \phi_t^{3/2}\right)\right]$$

Step 2 (Poole-Frenkel Emission):

$$R = A\cdot T^2 \exp\left(-\frac{E_T - \Delta\phi_T}{kT}\right)$$

$$where \quad \Delta\phi_T = \sqrt{\frac{q^3}{\pi\varepsilon_{AlGaN}E}}$$

O Mitrofanov et al. JAP, 95, 6414 (2004)

Step 2 (Phonon-Assisted Tunneling):

$$R = \frac{eE}{\left(8m^*\varepsilon_T\right)}\left[\left(1+\gamma^2\right)^{1/2} - \gamma\right]^{1/2}\left[1+\gamma^2\right]^{-1/4}$$

$$\times \exp\{-\frac{4}{3}\frac{\left(2m^*\right)^{1/2}}{eE\hbar}\varepsilon_T^{3/2}\left[\left(1+\gamma^2\right)^{1/2} - \gamma\right]^2$$

$$\times\left[\left(1+\gamma^2\right)^{1/2} + \frac{1}{2}\gamma\right]$$

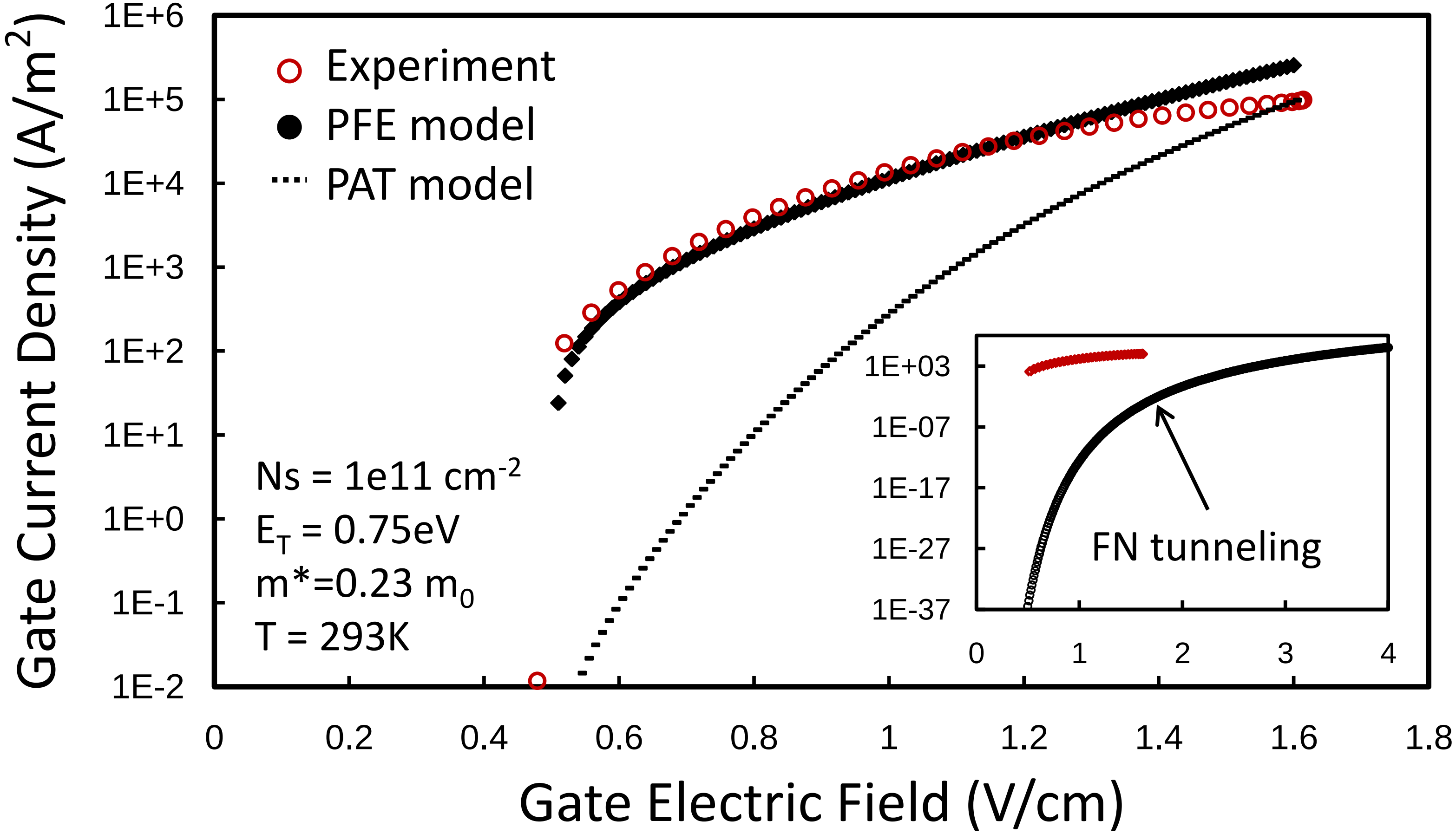
$$\gamma = \frac{\left(2m^*\right)^{1/2}\Gamma^2}{8e\hbar E\varepsilon_T^{1/2}}$$

$$\Gamma^2 = \Gamma_0^2\left(2n+1\right) = 8a\left(\hbar\omega\right)^2\left(2n+1\right)$$

$$n = \left[\exp\left(\hbar\omega/k_BT\right) - 1\right]^{-1}$$

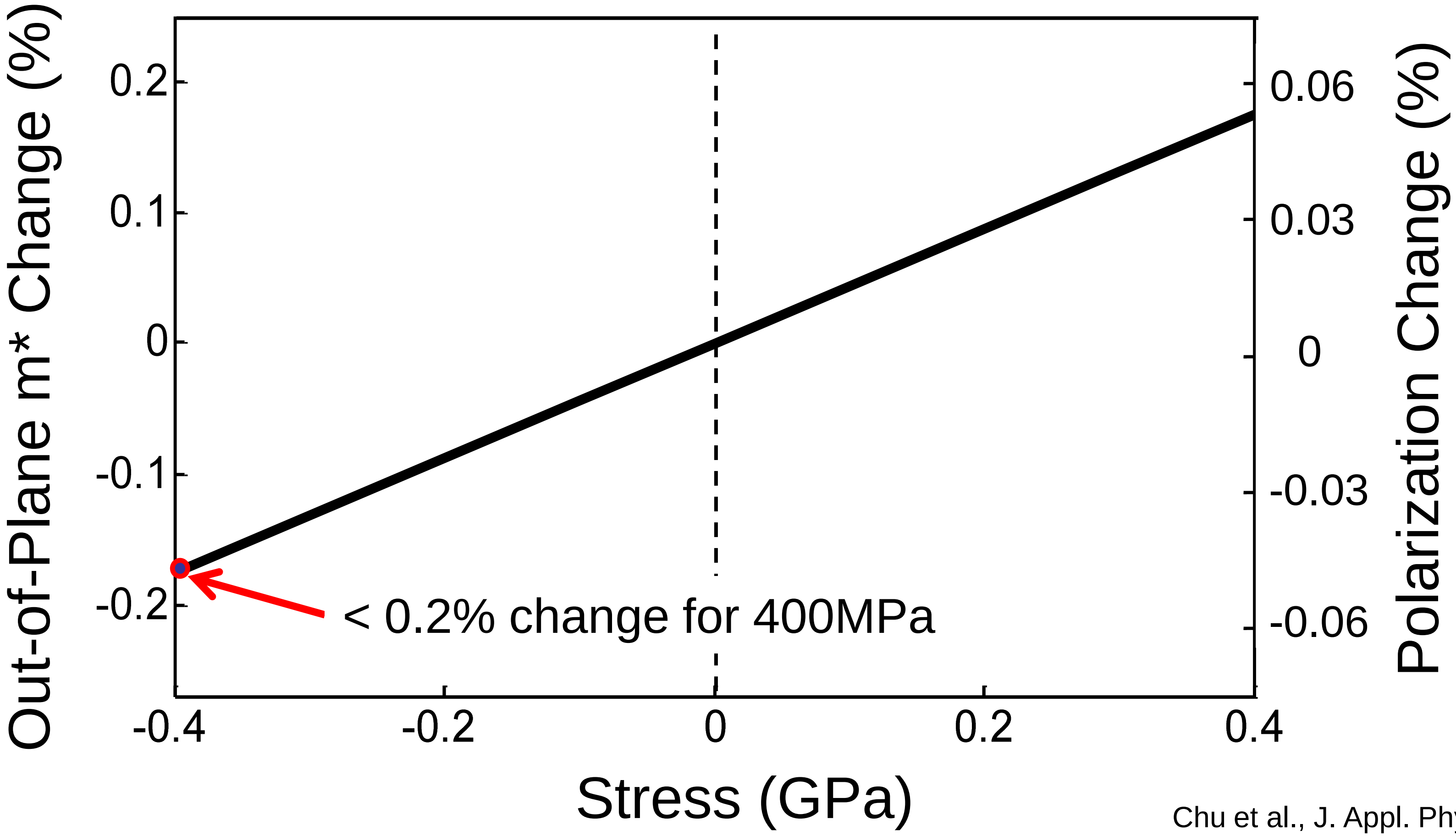
P Pipinys et al. JAP, 99, 093709 (2006)

Gate Leakage Simulation Result



Poole-Frenkel Emission is determined to dominate the gate leakage current in reverse-biased HEMT.

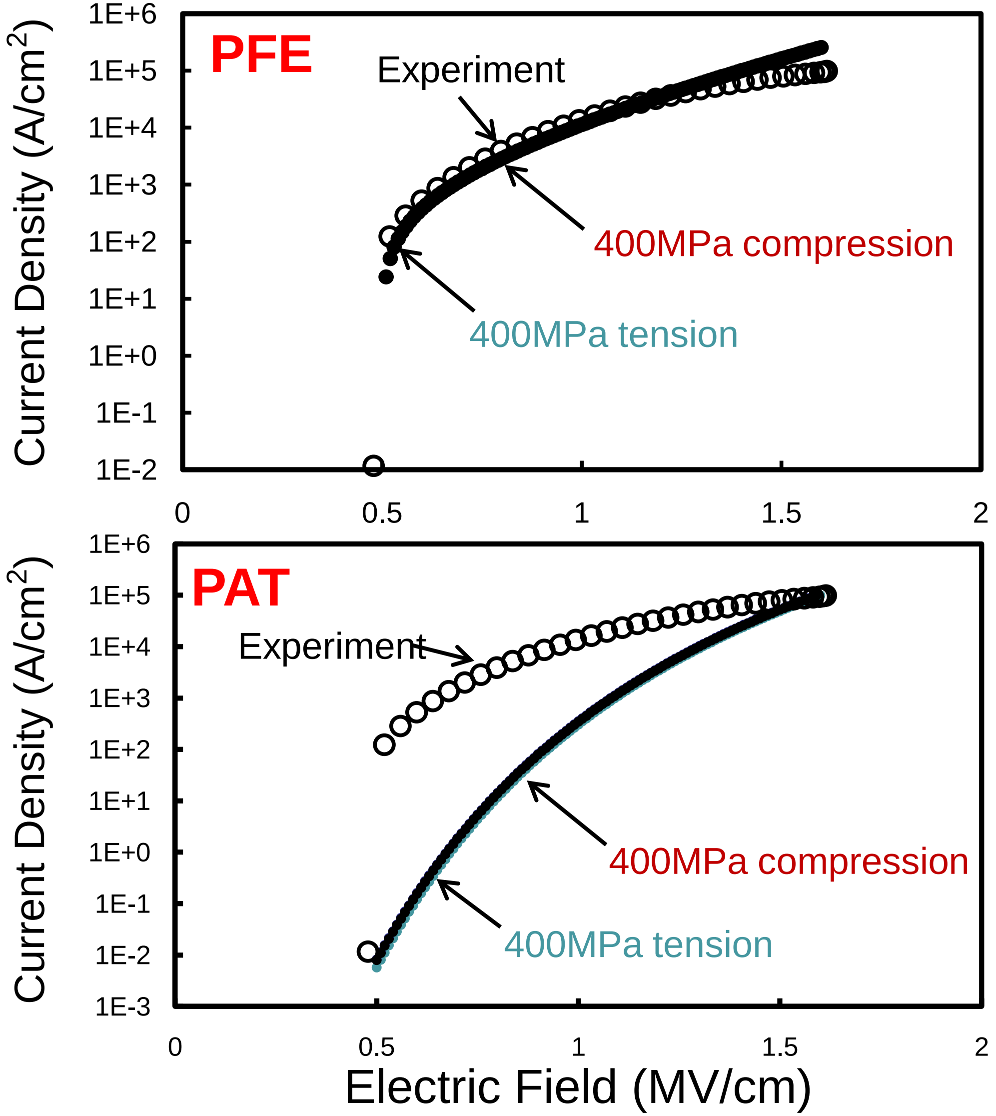
Effect of Stress on Mass and Field



Chu et al., J. Appl. Phys., 2010.

- sp^3d^5 tight-binding model was used to simulate m_{out}
- < 0.2% change in m_{out} under 400MPa
- < 0.06% change in polarization (E) under 400MPa

Effect of Stress-Altered Effective Mass on I_G



PFE: **0.3%** change for 400MPa

PAT: **1.7%** change for 400MPa

Experiment: ～3%/360MPa

- Only considered stress-altered effective mass and electric field.
- Stress-shifted trap level is expected to dominate the leakage current change.

Need to perform DFT calculation for defect levels with and without stress.

DFT (Density Functional Theory)

View energy as a function of electron density, instead of coordination.

First Theorem: Hohenberg and Kohn (Phys. Rev. 136, 864B, 1964)

- The ground state energy from Schrodinger's equation is a unique functional of the electron density.

Second Hohenberg and Kohn Theorem:

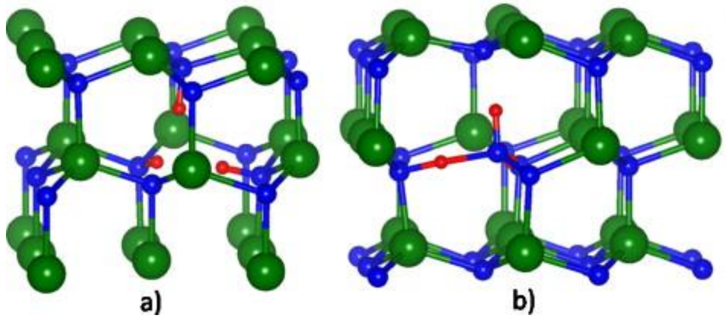
- The electron density that minimizes the energy of the overall functional is the true electron density corresponding to the full solution of the Schrodinger equation.

DFT calculation will be performed via **VASP**

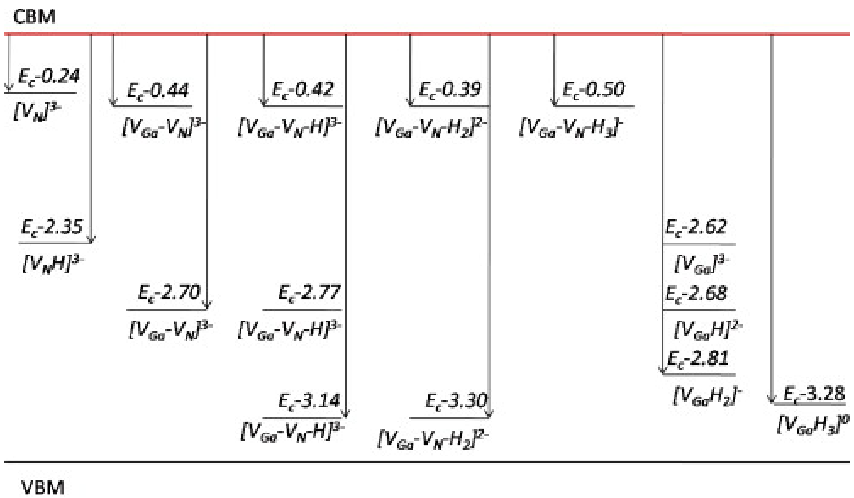
1. Define a supercell	POSCAR file
2. Choose potential approximation package	POTCAR file
3. Set k points in the reciprocal lattice	KPOINTS file
4. Set the cut off energy	INCAR file
5. Set mathematical treatments for results	INCAR file

Capability of DFT (Literature Review)

- **Relaxed lattice structure**

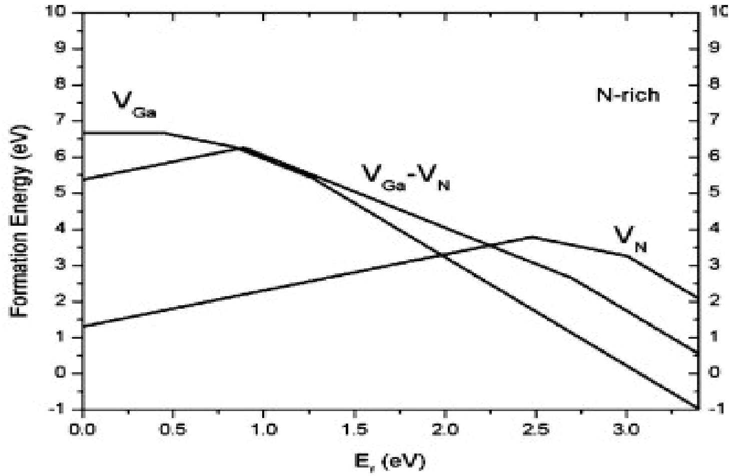


- **Defect level**

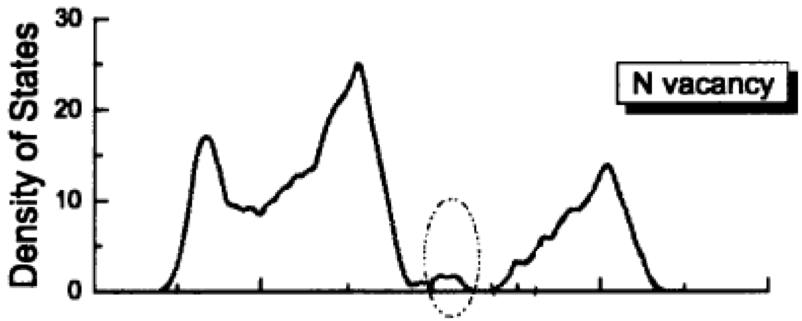


Puzyrev et. al. JAP, 109, 034501 (2011)

- **Defect formation energy**



- **Density of States**



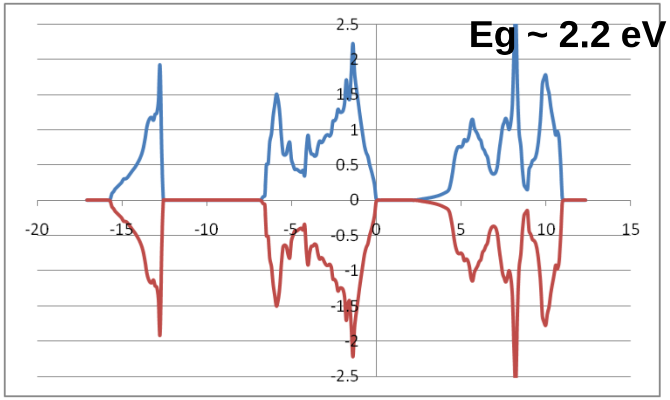
Lu et. al. SISPAD IEEE, 233-236 (2008)

DFT Results for Pure GaN

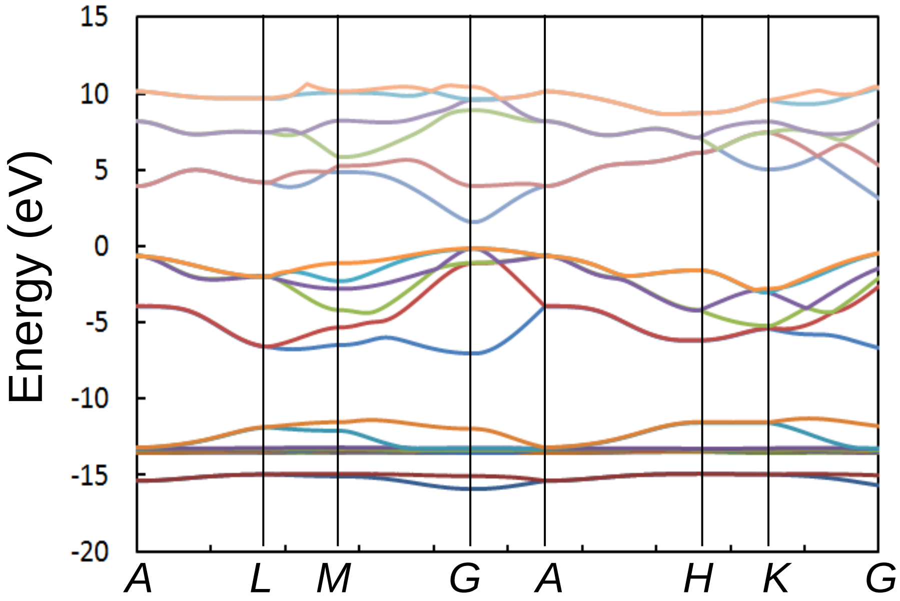
GaN

a (Å) **3.1937**

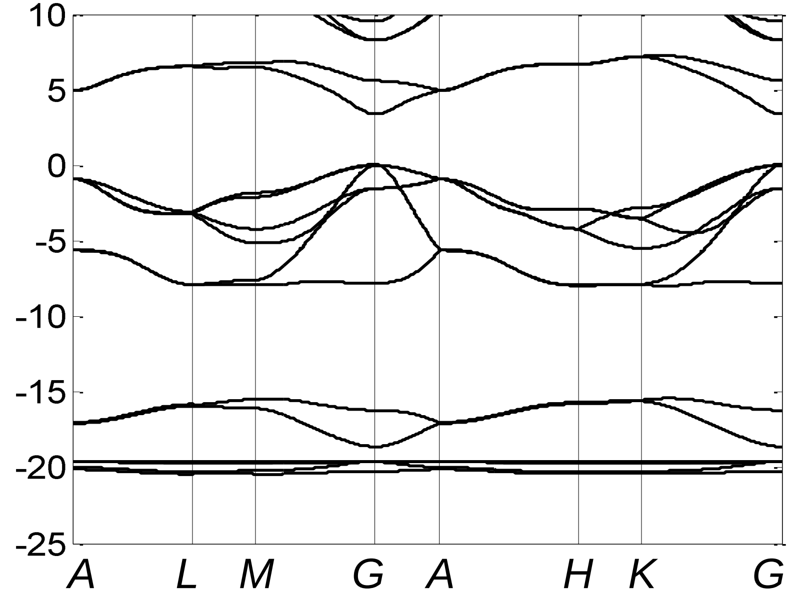
c (Å) **5.1935**



- PBE—GGA package
- Two N and two Ga atoms
- 8*8*8 k-points
- Cutoff energy = 382eV
- "Band gap problem"

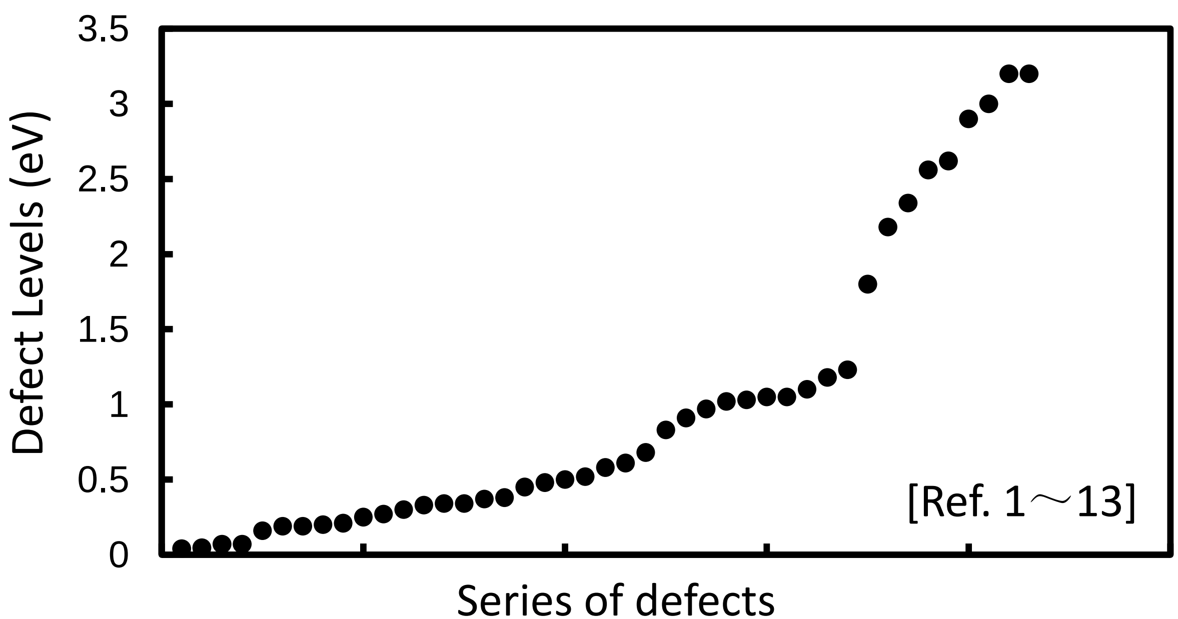


Tight binding method



DFT Calculation Plan

DFT
1. Pure GaN band structure with correct band gap
2. Defect levels without stress
3. Defect levels with stress



1) O. Fathallah et al. (2010)
2) M Gassoumi (2009)
3) M Marso (2003)
4) S Arulkumaran (2002)
5) AP Zhang (2002)
6) M Gassoumi (2006)
7) JG Tartarin (2007)
8) ST Bradley (2001)
9) M Wolter (2002)
10) T Okino (2004)
11) SY Park (2010)
12) ZQ Fanga (2005)
13) N Sghaier (2004)

Targeted defects:
1. native vacancies
2. Oxygen substituting N

Summary

- Investigated uniaxial longitudinal and transverse stress on J_G
- Determined E_{AlGaN} to analyze stress dependence of J_G
- Explained change in J_G with stress using change in trap energy in PF model
- Simulated reverse-biased gate leakage current based on FN, PFE, and PAT mechanisms
- Observed stress-altered effective mass has negligible effect on J_G
- Performed DFT calculation for pure GaN
- Collaborations underway to integrate mechanical and electrical stress experiments for t > 0

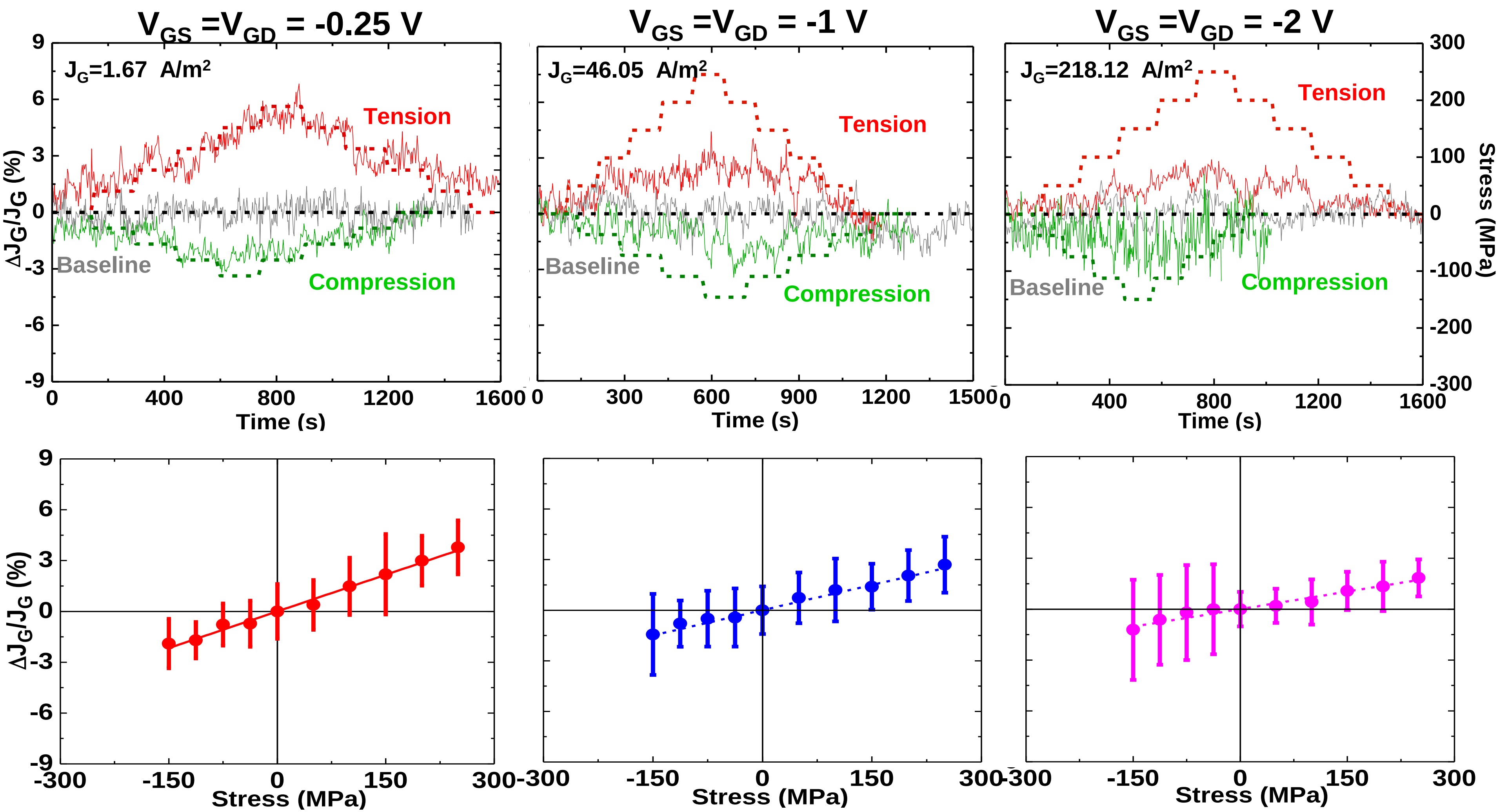
Acknowledgement

- We would like to thank Dr. Pearton, Dr. Ren, Dr. Gila, and Erica Douglas from Dept. of Material Science and Engineering, University of Florida for their help in electrical stressing of GaN HEMT samples.

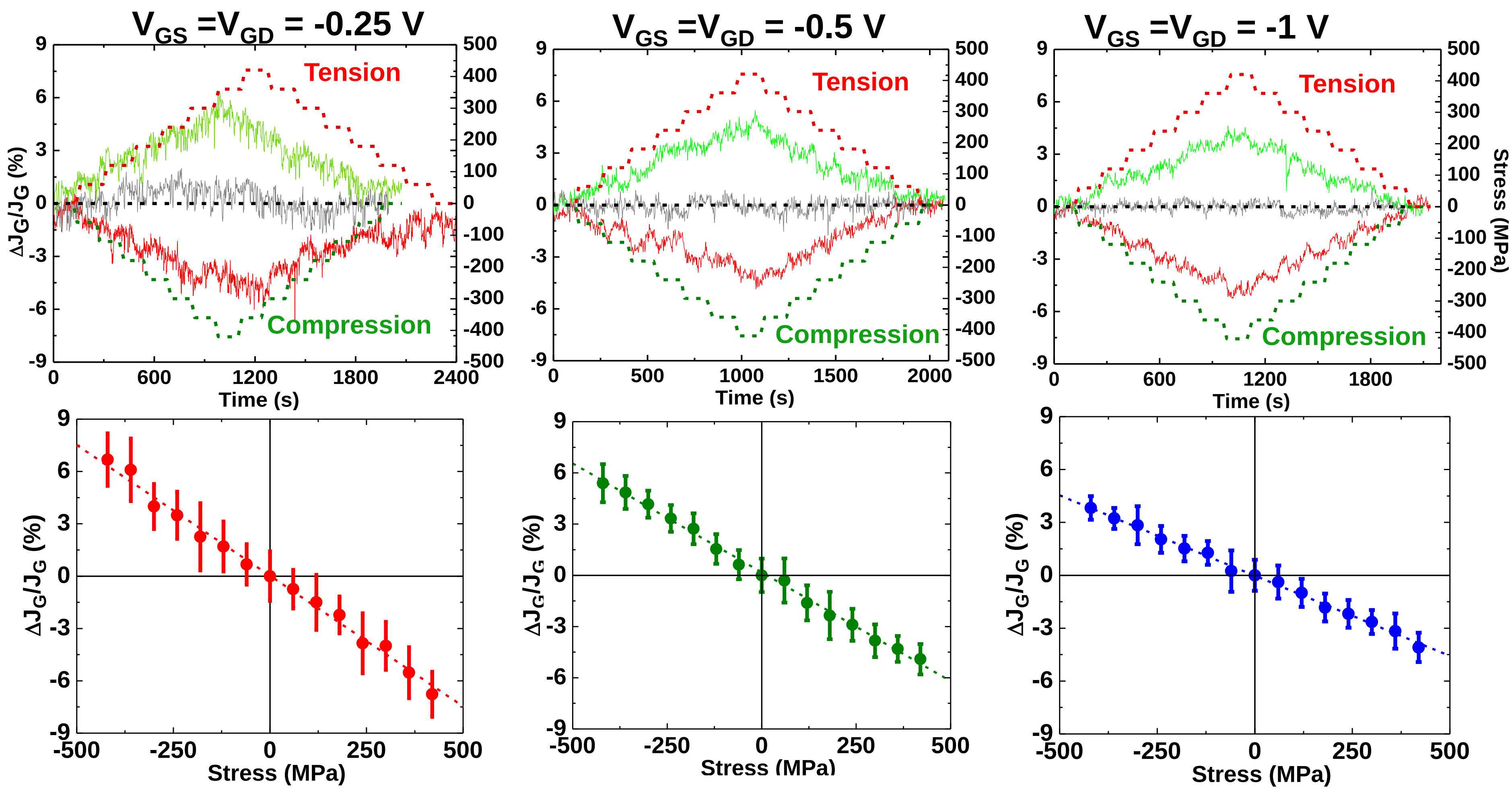
- We would like to thank Dr. Sinnott and Minki Hong from Dept. of Material Science and Engineering, University of Florida for their helpful instruction, suggestion, and discussion on the DFT calculation.

Backup Slides

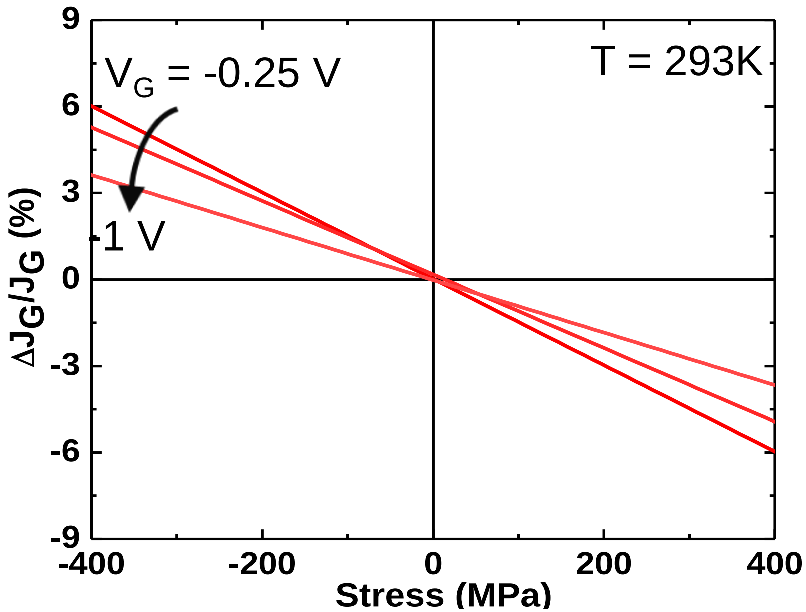
J_G Longitudinal Stress Measurement Results (AFRL)



J_G Transverse Stress Measurement Results (AFRL on Si)



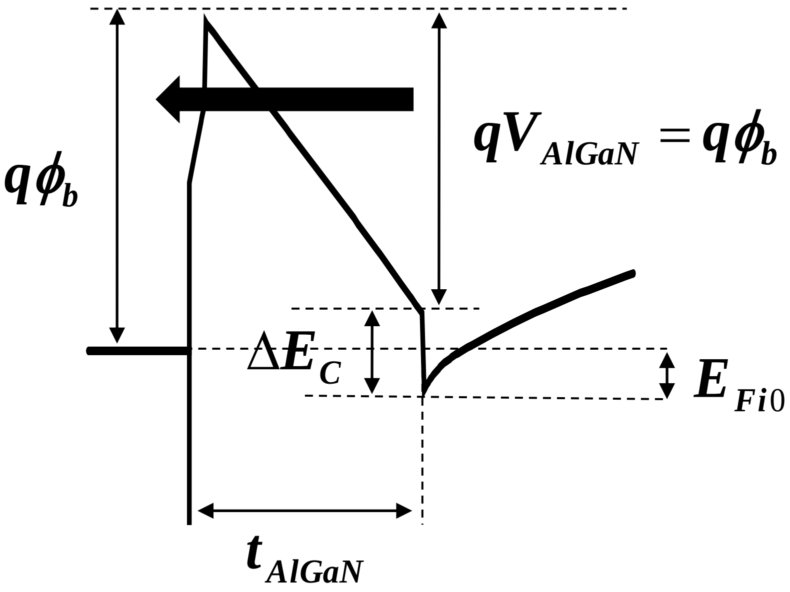
Summary Of Transverse Stress Effect



	V_G=-0.25 V	V_G=-0.5 V	V_G=-1 V	V_G=-2 V	V_G=-4 V
AFRL on Si $\Delta J_G/J_G$ (% / 100 MPa) (Transverse stress)	-1.50	-1.28	-0.92		
Commercial $\Delta J_G/J_G$ (% / 100 MPa) (Longitudinal stress)	1.68	1.40	1.17	0.88	0.62
AFRL on SiC $\Delta J_G/J_G$ (% / 100 MPa) (Longitudinal stress)	1.50	1.30	1.00	0.70	

Derivation of E_{AlGaN}

$$E_{AlGaN} = V_{AlGaN} / t_{AlGaN}$$



$$qV_{AlGaN} = q\phi_b - \left(\Delta E_C - E_{Fi0}\right)$$

$$E_{AlGaN} = \frac{V_{AlGaN}}{t_{AlGaN}} = \frac{\phi_b - \left(\Delta E_C - E_{Fi0}\right)}{t_{AlGaN}}$$

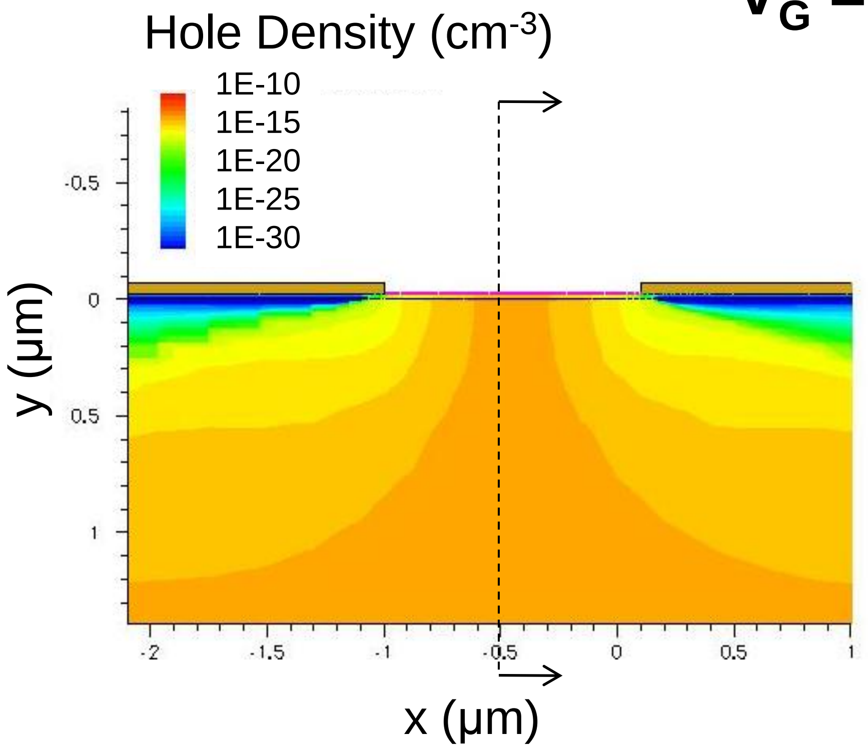
$$n_s = \frac{Q_{TOT}}{q} - \frac{C_{AlGaN}}{q^2}\left[q\phi_b + E_{F0} - \Delta E_C\right]$$

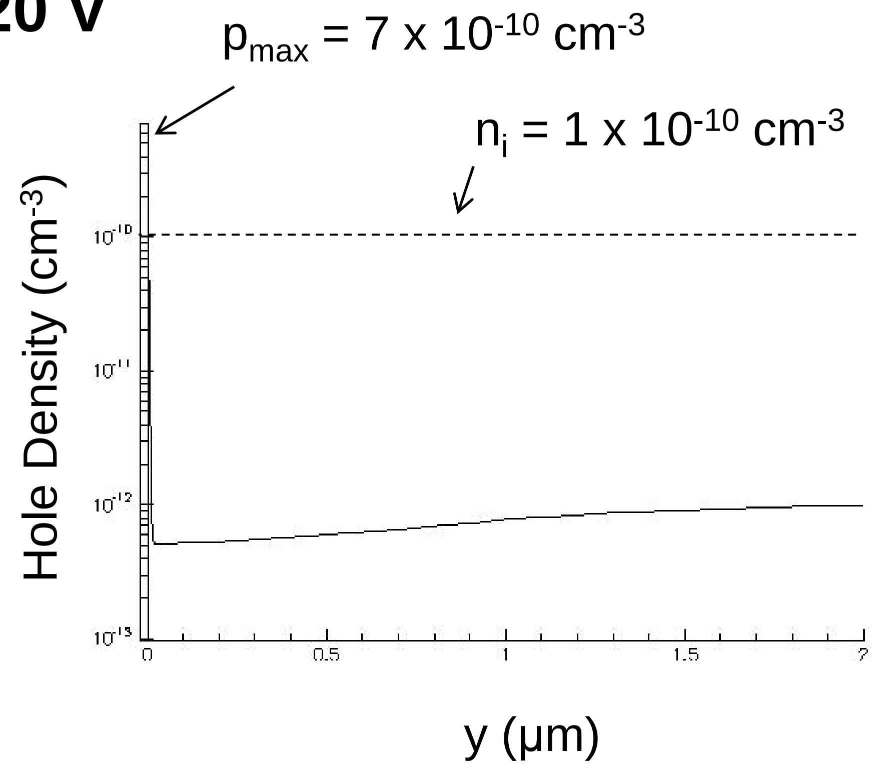
$$qn_s = Q_{TOT} - \varepsilon_{AlGaN} E_{AlGaN}$$

$$E_{AlGaN} = \frac{Q_{TOT} - qn_s}{\varepsilon_{AlGaN}}$$

Hole Density Under Large Reverse Bias

V_G = -20 V





- There is no source of holes for accumulation (n_i = 1 x 10^{-10} cm^{-3})
- 2DEG electrons come from surface states under gate, not from substrate